Performance Characteristics of the NSTAR Ion Thruster During an On-Going Long Duration Ground Test

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Abstract—A long-duration test of the Deep Space 1 (DS1) flight spare thruster (FT2) is presently being conducted. To date, the thruster has accumulated over 6700 hours of operation. Performance data—such as thrust, specific impulse and efficiency—over the full 0.5 to 2.3 kW throttling range are presented. Comparison of FT2 with the performance of the engineering model thruster 2 (EMT2) during an 8.2 khr test shows a transient, lasting for about 3000 hours, during which the discharge chamber efficiency decreases for both thrusters. After the initial transients decay, the performance of both thrusters at full power is comparable with the exception of the electron backstreaming limit, which is 6 V lower for FT2. Degradation of electrical isolation for neutralizer and for discharge cathode components has occurred during FT2 testing; although this has made starting the thruster slightly more difficult, it is not expected to cause thruster failure.

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1. Introduction

NASA's 30 cm diameter xenon ion thruster technology is being validated for use in planetary missions by the NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) program. This program is designed to develop the industrial capability to produce flight engine, power processor, and propellant feed system hardware and demonstrate that the technology is mature enough for flight applications. One of the goals of the program is to provide flight managers with sufficient information on performance, thruster life and spacecraft interactions to give them the confidence to use the technology.

The technology validation includes a number of ground tests designed to demonstrate engine performance over the required throttling range, characterizing the engine and plume interactions with the spacecraft, and understanding the dominant failure modes. The program includes 4 long-duration ground based tests and in-flight validation of the xenon ion thruster technology on the Deep Space 1 (DS1) spacecraft.

During the first long-duration ground test, 2000 hours [1] of operation were accumulated at the NSTAR full power point (2.3 kW thruster power). During this test several potential failure modes were identified and subsequently studied in shorter duration tests. Design changes, made as a result of this work, were then validated in a 1000-hour wear test at full power [2]. Subsequent to this test, an engineering model thruster, designated EMT2, was tested for 8200 hours at the NSTAR full power point [3,4]. During the execution of this test, two flight thrusters were fabricated by Hughes Electron Dynamics Division; short duration acceptance and qualification testing were subsequently performed on these thrusters [5,6].

After qualification testing, one of the flight thrusters, designated FT1, was integrated onto the DS1 spacecraft. On October 24, 1998 the DS1 spacecraft was launched. Operation of FT1 began in November 1998; after thrusting for over 1800 hours and processing 12.6 kg of xenon, the DS1 spacecraft performed a flyby of asteroid 9969 Braille on July 28, 1999. Processing an additional 68 kg of xenon with FT1 is planned, so that DS1 can flyby comet Wilson-Harrington and comet Borrelly in January 2001 and September 2001, respectively. A discussion of the operation and performance of FT1 on the DS1 spacecraft is given in Ref. [7].

Modifications to the EMT design, due to thermal and structural considerations, were incorporated into the flight thrusters [5]. Although these modifications were not expected to cause significant change in thruster performance, ground testing of the spare flight thruster, designated FT2, was initiated before the launch of DS1. Initial testing was done to determine if there were any significant problems with the flight thruster design prior to the launch of DS1. Ground testing of FT2 began on October 5, 1999 and 412 problem free hours of operation were accumulated before the DS1 launch. Life testing of FT2 has continued since the DS1 launch to identify potential problems before they occur on DS1 and to further study known thruster wear out modes. Most of the testing through the first 4937 hours was conducted at the NSTAR full power point. Since then the thruster has been operated at 1.5 kW thruster power.

2. Test Plan

A major objective of the FT2 test is processing 125 kg of xenon, which is 150% of the NSTAR thruster design life. Based on the condition of EMT2 after processing 88 kg of xenon at full power [4], it is thought that FT2 is capable of demonstrating the additional life. The larger throughput per thruster is required to enable ambitious solar system exploration missions. Proposed missions include Europa Lander, Neptune Orbiter, Saturn Ring Explorer, Venus Sample Return and Comet Nucleus Sample Return.

Many of these missions require throttling the thruster over a range of 0.5 to 2.3 kW, so it is desirable to conduct testing at throttled operating conditions. During a typical mission, the thruster power is throttled in small increments to use the maximum available solar power. However, to facilitate comparison of experimental data with thruster performance models, FT2 testing will be conducted with relatively long periods of operation at chosen power levels. Testing at throttled conditions is also done to study thruster wear characteristics, and to identify potential failure modes or operational difficulties not observed during full power testing.

In addition to normal operation, short duration throttling tests are conducted at intervals. During these tests, thruster performance is measured at six points covering the 0.5 to 2.3 kW operating range.

Testing of FT2 prior to the DS1 launch was conducted at 1.96 kW, which was the maximum power available for thruster operation on DS1. Shortly after the DS1 launch, at 448 hours, the throttle level was increased to 2.3 kW and operation at this level continued until 4937 hours. At that point 51 kg of xenon had been processed by FT2. The thruster was then throttled to 1.5 kW and has operated at this level since. The present plan is to operate at 1.5 kW for the next 40 kg (~6,000 hours at 1.5 kW). Then resumption of full power operation, to process an additional 40 kg of xenon by the end of calendar year 2000, is planned.

If additional funding were available, it would be desirable to change the plan and execute FT2 testing near the minimum power level (somewhere between 0.5 and 0.8 kW) for an extended period. As with the other power levels, this testing would be done to gain additional insight into thruster wear mechanisms as well as identify failure modes or operational difficulties.

3. Thruster

A schematic diagram of the 30-cm-diameter NSTAR flight thruster is shown in Fig. 1. The thruster is comprised of four major components; these are the discharge cathode, the discharge chamber, the ion optics and the neutralizer cathode. The thruster operates by ionizing xenon propellant in the discharge chamber and then accelerating the positive ions through the ion optics system. The neutralizer cathode supplies electrons to charge neutralize the ion beam.

Laboratory power supplies are being used for FT2 testing. These supplies have similar capabilities to those used on the DS1 spacecraft; however, there are some differences which will be noted. Xenon feed lines, shown in Fig. 1, are at facility ground potential for FT2 testing and are at spacecraft ground potential on DS1. The thruster is electrically isolated from the feed lines by a ceramic propellant isolator in each line. The thruster and power supplies are electrically isolated from facility ground for FT2 testing and are isolated from spacecraft ground on DS1. The thruster reference potential, for both FT2 in ground testing and FT1 on DS1, is neutralizer common.

The thruster start sequence begins by flowing xenon propellant at the full power setpoint values through each of

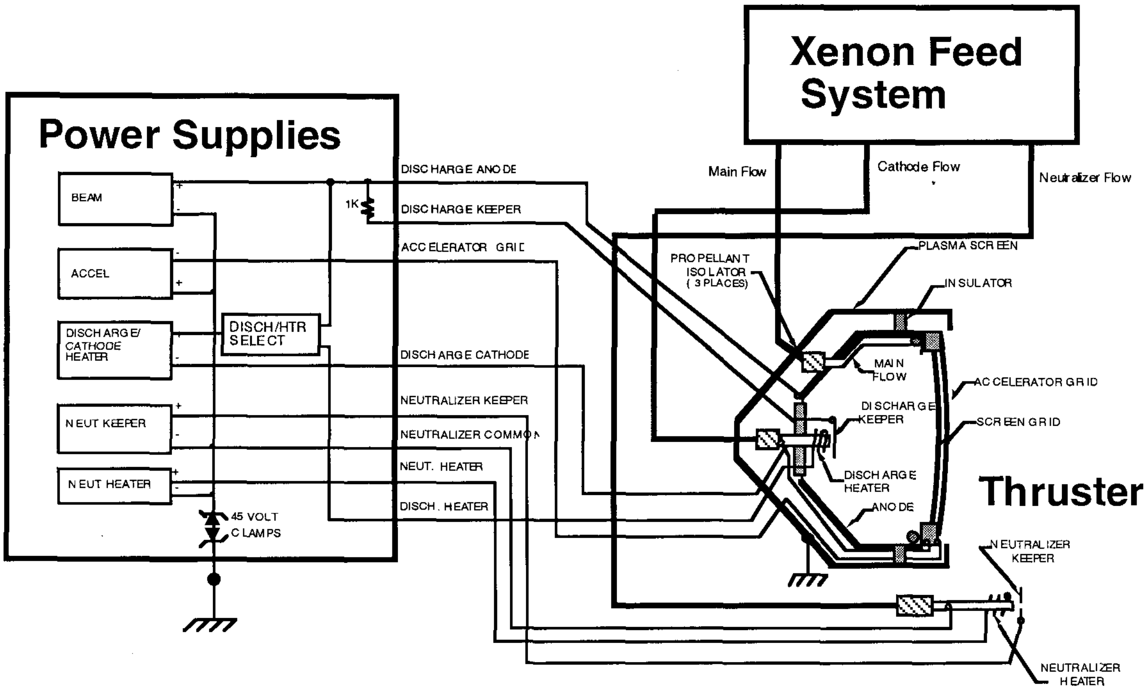

Fig. 1: Schematic of FT2.

the three feed lines. Once steady flow has been established, the current regulated neutralizer heater and discharge cathode heater supplies are both commanded to 8.5 A. After 210 seconds of heating, the current regulated neutralizer keeper supply (35 V open circuit) is commanded to 2 A and is enabled. The neutralizer hollow cathode is enclosed inside the neutralizer keeper electrode which has an orifice at the downstream end to allow xenon (and plasma when the neutralizer is ignited) to flow away from the neutralizer. On DS1 a 650 V, 10 μs pulse supply, with a 10 Hz repetition rate, is also turned on to facilitate striking an arc between the neutralizer hollow cathode and the neutralizer keeper. For FT2 testing a pulse supply of the same design is available. Once the neutralizer discharge is ignited, the neutralizer heater and the pulse start supply are both turned off and the neutralizer operates in a self-heating mode. The plasma produced by the neutralizer bridges the gap between the neutralizer hollow cathode and the neutralizer keeper electrode allowing electrons to flow to the neutralizer keeper. During normal thruster operation, the neutralizer plasma also bridges the gap between the neutralizer and the ion beam allowing charge neutralizing electrons to flow into the positive beam.

On DS1, after the neutralizer is started the current regulated discharge supply (35 V open circuit) is commanded to 4 A and is enabled. A pulse start supply, similar to the neutralizer pulse supply, is used to apply a 650 V pulse between the anode and discharge cathode. The discharge cathode keeper is connected to the anode through a 1 kΩ resistor and the arc discharge is started between the discharge hollow cathode and the discharge cathode keeper. Once the discharge is started the cathode heater and the pulse start supply are turned off and the discharge cathode operates in a self-heating mode.

For FT2 testing, the discharge power supply is used to operate both the cathode heater and the discharge. After the neutralizer is started, the current regulated discharge supply is turned off. Then a relay is enabled to switch the power supply from the cathode heater to the anode. Then the discharge supply (50 V open circuit) is commanded to 4 A and it is enabled. In the FT2 test the anode is also connected to the discharge cathode keeper through a 1 kΩ resistor so that the discharge can be started between the discharge hollow cathode and the discharge keeper. If the discharge does not ignite using the discharge supply, a 250 V start supply can be used for FT2.

During normal thruster operation, xenon—which is fed into the discharge chamber through the spun titanium anode main flow line and through the discharge cathode flow line—is ionized by energetic electrons supplied by the discharge cathode. To improve the ionization efficiency of the discharge chamber, a magnetic field provided by three rings of rare-earth permanent magnets is used. The back magnet ring is mounted behind the discharge chamber cathode. The middle ring is attached at the upstream end of the cylindrical section of the discharge chamber. The front magnet ring is attached near the ion optics system.

Once positive xenon ions are being produced in the discharge chamber, the voltage regulated beam and accelerator supplies are turned on to set up an electric field in the two-grid molybdenum ion accelerator system (or ion optics system) attached to the downstream end of the discharge chamber. The upstream grid (called the screen grid) is tied to discharge cathode common potential. The voltage regulated beam supply is used to bias the discharge chamber as much as 1100 V above neutralizer common during normal thruster operation. Positive xenon ions are accelerated toward and focused through apertures in the downstream grid (called the accelerator grid). The accelerator grid is typically biased 150 to 250 V negative of neutralizer common to keep beam-neutralizing electrons from flowing upstream through the ion optics into the discharge chamber. To prevent beam-neutralizing electrons from reaching high voltage exterior surfaces, the discharge chamber is enclosed in a perforated plasma screen. The plasma screen is tied to facility ground in ground based testing and is tied to spacecraft common in flight. For the ground test, the thruster is mounted to a holding fixture (at facility ground potential) with three equally spaced gimbal pads, while on the spacecraft it is mounted on a gimbal ring (tied to spacecraft ground).

The flight thrusters incorporate several minor design changes which are not included in the EMT2 design [5]. In the EMT2 design the discharge chamber is fabricated from spun aluminum and titanium parts, while the flight design uses titanium for the entire discharge chamber. In addition, the gimbal brackets used to attach the thruster to the spacecraft have been changed from stainless steel in EMT2 to titanium and some of the discharge chamber components have lightening holes in the flight design. Grit-blasted wire mesh, which covers the upstream conical portion of the discharge chamber for improved sputter containment in EMT2, has been extended to cover the downstream portion as well in the flight design. Many of the components in the flight thruster are grit blasted to improve thermal radiation capability compared to EMT2. The flight design also uses magnets which have been thermally stabilized at a higher temperature than those used in EMT2. In EMT2 the main cathode keeper assembly is attached to the discharge chamber, while the flight design uses a brazed cathode-keeper assembly. These design changes were validated by analysis or short duration tests and were not expected to have a negative impact on engine performance or wear characteristics.

4. Throttle Table

Table 1 shows the set points for each of the seven independent operating parameters for the NSTAR thruster. Additional columns showing the NSTAR throttle level designation and the nominal thruster power are also included. The power level designation is given as a TH level, ranging from TH0 for 0.5 kW to TH15 for 2.3 kW.

The propellant exhaust velocity is controlled by the beam voltage. The beam current is proportional to the rate at which propellant mass is extracted and accelerated from the thruster. The discharge power supply current set point is controlled to produce the ions required to provide the desired beam current. The accelerator grid voltage is set negative enough to prevent electron backstreaming. The neutralizer keeper current is set to ensure that the neutralizer does not extinguish during recycle events. Occasionally an arc occurs between high voltage surfaces and ground or between the screen and accelerator grids. A recycle event is said to

Table 1: NSTAR Thruster Throttle Table

NSTAR Throttle Level	Nominal Thruster Power	Beam Supply Voltage	Beam Current	Accelerator Grid Voltage	Neutralizer Keeper Current	Main Flow	Discharge Cathode Flow	Neutralizer Cathode Flow
	kW	V	A	V	A	sccm	sccm	sccm
TH 0	0.52	650	0.51	-150	2.0	5.98	2.47	2.40
TH 1	0.66	850	0.53	-150	2.0	5.82	2.47	2.40
TH 2	0.75	1100	0.52	-150	2.0	5.77	2.47	2.40
TH 3	0.91	1100	0.61	-150	2.0	6.85	2.47	2.40
TH 4	1.02	1100	0.71	-150	2.0	8.30	2.47	2.40
TH 5	1.12	1100	0.81	-150	2.0	9.82	2.47	2.40
TH 6	1.24	1100	0.91	-150	2.0	11.33	2.47	2.40
TH 7	1.34	1100	1.00	-150	2.0	12.90	2.47	2.40
TH 8	1.46	1100	1.10	-180	1.5	14.41	2.47	2.40
TH 9	1.58	1100	1.20	-180	1.5	15.98	2.47	2.40
TH10	1.72	1100	1.30	-180	1.5	17.22	2.56	2.49
TH11	1.85	1100	1.40	-180	1.5	18.51	2.72	2.65
TH12	1.96	1100	1.49	-180	1.5	19.86	2.89	2.81
TH13	2.08	1100	1.58	-180	1.5	20.95	3.06	2.98
TH14	2.20	1100	1.67	-180	1.5	22.19	3.35	3.26
TH15	2.33	1100	1.76	-180	1.5	23.43	3.70	3.60

occur when the beam and accelerator grid power supplies are briefly turned off, in response to the overcurrent caused by the arc, and then turned back on after the arc has extinguished.

The main flow and discharge cathode flow rates are set to maintain near optimal discharge chamber performance. If the flow rate is decreased while the beam current is held constant, the discharge power required to produce the ions needed for the ion beam increases. If the flow rate is increased while the beam current is held constant, the amount of neutral propellant leaking through the grids increases. The neutral gas escaping from the thruster is not accelerated to high velocity and does not contribute significantly to the thrust. The flow rates are set to a level where the trade between neutral propellant loss and discharge power results in near optimal discharge chamber performance.

It is desirable to minimize the neutralizer flow rate because the propellant expended through the neutralizer is not used to produce thrust. The neutralizer flow is used to produce a low impedance plasma bridge between the neutralizer and the ion beam. If the flow is reduced too much, the impedance becomes large and the charge-neutralizing electrons have difficulty reaching the beam. Typically, large voltage oscillations occur when this happens and these oscillations can result in damage to the neutralizer. These oscillations are characteristic of what is referred to as plume mode operation. The neutralizer flow rates are set to minimize propellant loss while maintaining enough margin to prevent plume mode operation.

5. Vacuum Facility

The long-duration test of FT2 is being conducted in a 3-m-diameter by 10-m-long vacuum chamber pumped by three 1.2-m-diameter CVI cryopumps with a combined pumping speed of 45-50 kL/s on xenon. In addition, three xenon cyropumps [8] consisting of 0.7 m^2 pure aluminum panels mounted on Cryomech AL200 coldheads, each with a xenon pumping speed of 18 kL/s, are used for a total xenon pumping speed of 100 kL/s. This pumping system provides a base pressure of $1x10^{-5}$ Pa ($1x10^{-7}$ Torr) and less than $5x10^{-4}$ Pa ($4x10^{-6}$ Torr) at the full power flow rates. After the six pumps accumulate a total of about 10 kg of xenon, the pumping surfaces must be regenerated. This exposes the engine to an atmosphere composed primarily of xenon at a pressure of about 4000 Pa (30 Torr). The cathodes are purged with xenon during these exposures and are reconditioned after the subsequent pumpdown to high vacuum. After the pump regeneration, there is usually a temporary increase in neutralizer keeper voltage and in the magnitude of the coupling voltage.

To reduce the amount of facility material backsputtered onto the engine , the walls and rear of the vacuum chamber are lined with graphite panels. The backsputtered deposition rate is monitored with a quartz crystal microbalance located next to the engine in the plane of the grids. At full power the backsputter rate is 0.16 mg/cm^2 khr or 0.7 μm/khr.

The propellant feed system has two Unit Instruments mass flow meters in each of the main, cathode and neutralizer flow lines. All six of these meters are mounted on a temperature controlled plate inside a thermally insulated box. The downstream flow meter in each line is used to measure the flow rate to an accuracy of ±1 percent. The upstream flow meters are used as flow controllers. The output signal from each controller is used to actuate a solenoid valve which maintains the flow rate at the setpoint in each line. The solenoid valves are mounted on a second temperature controlled plate which is installed in an evacuated box. The feed system lines from the evacuated box through the vacuum chamber walls to the thrust stand are all welded to eliminate air leaks into the low pressure part of the flow system. At the thrust stand, located inside the vacuum chamber, resistoflex fittings are used to connect the feed lines to the thruster. The flow meters are calibrated on xenon, after each cryopump regeneration.

Laboratory power supplies are being used to run the thruster during this test. These supplies are the same ones used for the 1,000 hour test [2] and for the last 5,200 hours of the 8,200 hour test [4]. A computer data acquisition and control system is used to monitor facility and engine conditions as well as control the power supplies. Engine electrical parameters are measured to within ±0.5 percent using precision shunts and voltage dividers which are calibrated during each cryopump regeneration. The system samples and stores data at ~5 second intervals. It is programmed to shut down the thruster if facility problems occur or out-of-tolerance conditions on certain engine parameters occur. This allows the system to be operated in unattended mode.

At present, work is being conducted to allow unattended operation of the thruster on the DS1 flight spare power processing unit (PPU). The PPU will be operated in a vacuum facility located adjacent to the thruster chamber. The PPU is mounted on a temperature controlled plate and was recently used to run the thruster during attended, short duration testing. Installation of interlocks that will shut down the thruster and PPU if facility problems are detected is nearing completion. During preparation of the PPU facility, the PPU has been used for grid clear testing to support the DS1 mission [9].

6. Diagnostics Equipment

A thrust vector probe [10] used to monitor the thrust vector is located 5.8 m downstream of the thruster. The probe consists of 16 horizontal and 16 vertical 9-mm-diameter by 1.2-m-long graphite rods configured in a square array. The rods are evenly spaced 7 cm apart and are biased 20 V negative of facility ground to repel electrons. The current to each rod represents the integral across the beam current density distribution at a given location. The currents to the vertical or horizontal rods can be fit with gaussian distributions. The intersection of the centriods of these distributions defines the location of the thrust vector.

An ExB probe, mounted 6 m downstream of the thruster, is used to measure the double-to-single ion current ratio. The probe collimator samples ions emitted from a rectangular strip 1.8 cm wide in one direction and extending across the entire diameter of the thruster in the other direction. The probe is mounted on a turntable. By adjusting the turntable the cross-section of the thruster from which ions are sampled can be varied. The probe was aligned with the thruster operating and was pointed in the direction which yielded the maximum single ion current.

7. Test Results

Testing of FT2 is being conducted to measure thruster performance changes over the life of the thruster and identify potential failure modes. Among the data presented are throttling test data, over the full 0.5 to 2.3 kW range. Also, comparison of FT2 performance against that of the engineering model thruster, EMT2, during the 8200 hour life test is described. Additional details are presented in Ref. 14. A decrease in the electrical isolation between discharge cathode and neutralizer cathode components has occurred during FT2 testing; the impact on thruster performance and life is discussed.

Throttling Test Results

Results of throttling tests over the power range (0.5 kW to 2.3 kW thruster power) are shown in Figs. 2, 3 and 4. These data are also presented in Table 2. Figure 2 shows the thrust as a function of thruster power at several times during the test. The thrust is primarily a function of beam current (proportional to mass flow rate) and the square root of the beam voltage (proportional to ion speed). Since both beam current and beam voltage are set to fixed values, the thrust level is also fixed. Variations in thruster power required to produce a given thrust are due primarily to changes in the discharge power as the thruster wears. The beam voltage is 1100 V at all but the lowest power point at which it is 650 V.

The specific impulse variation with thruster power is shown in Fig. 3. Specific impulse is defined as the thrust divided by the propellant weight flow rate at the surface of the earth. At the minimum power point the specific impulse is low primarily because the beam voltage is low (650 V compared to 1100 V at all other operating conditions). At the power levels between 0.5 and 1.5 kW

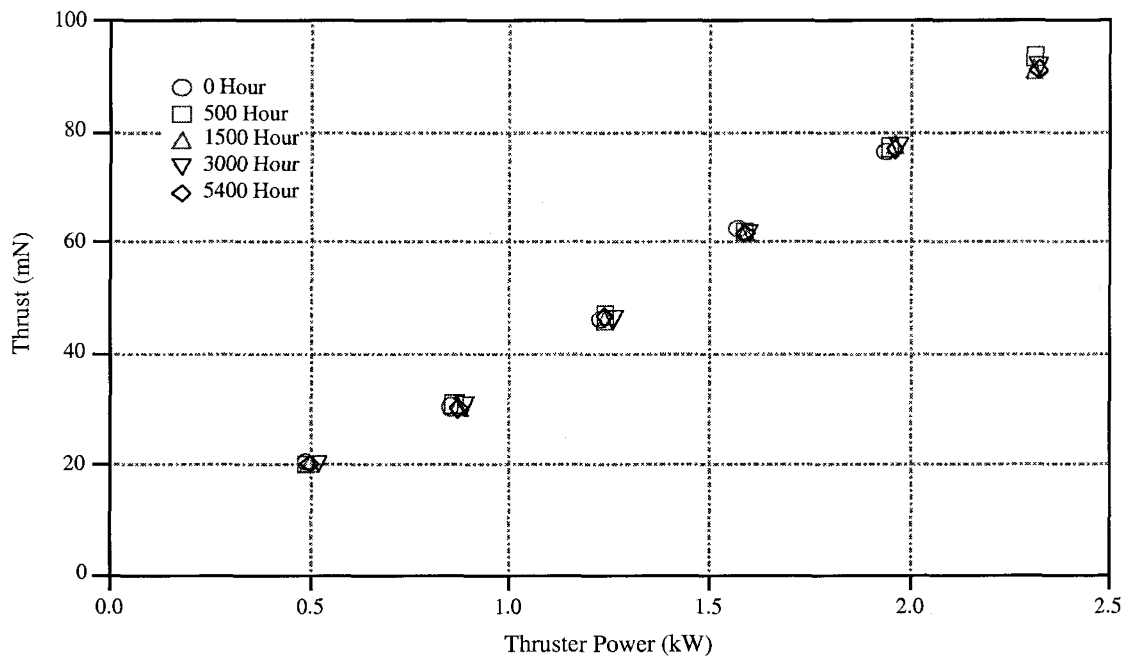

Fig. 2: FT2 Thrust vs Power

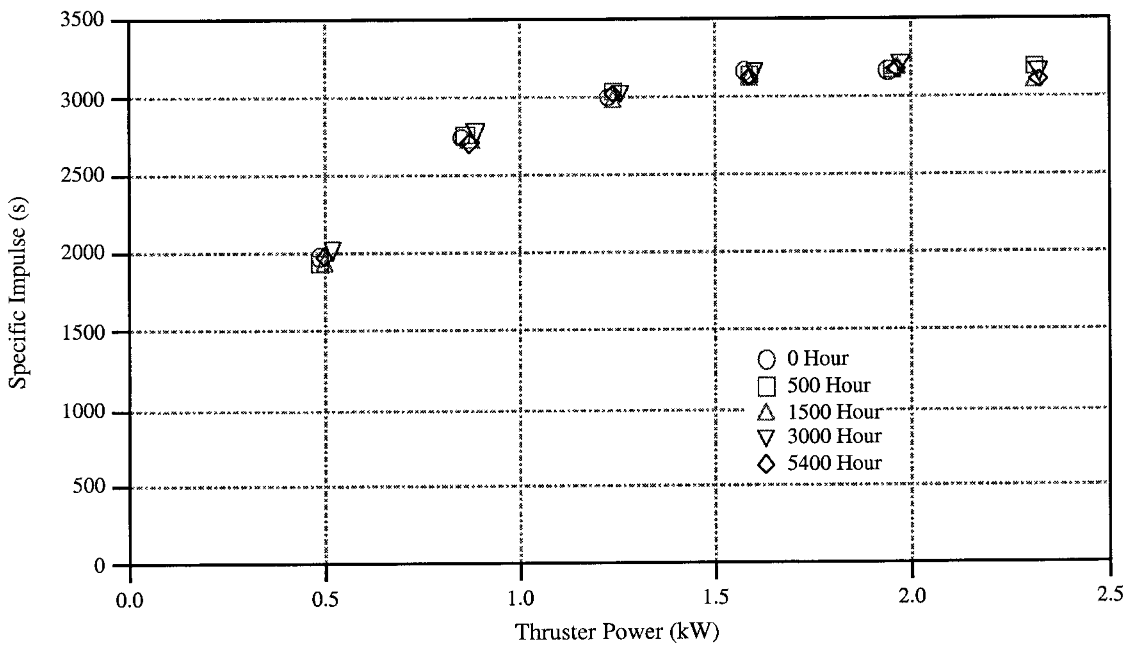

Fig. 3: FT2 Specific Impulse vs Power

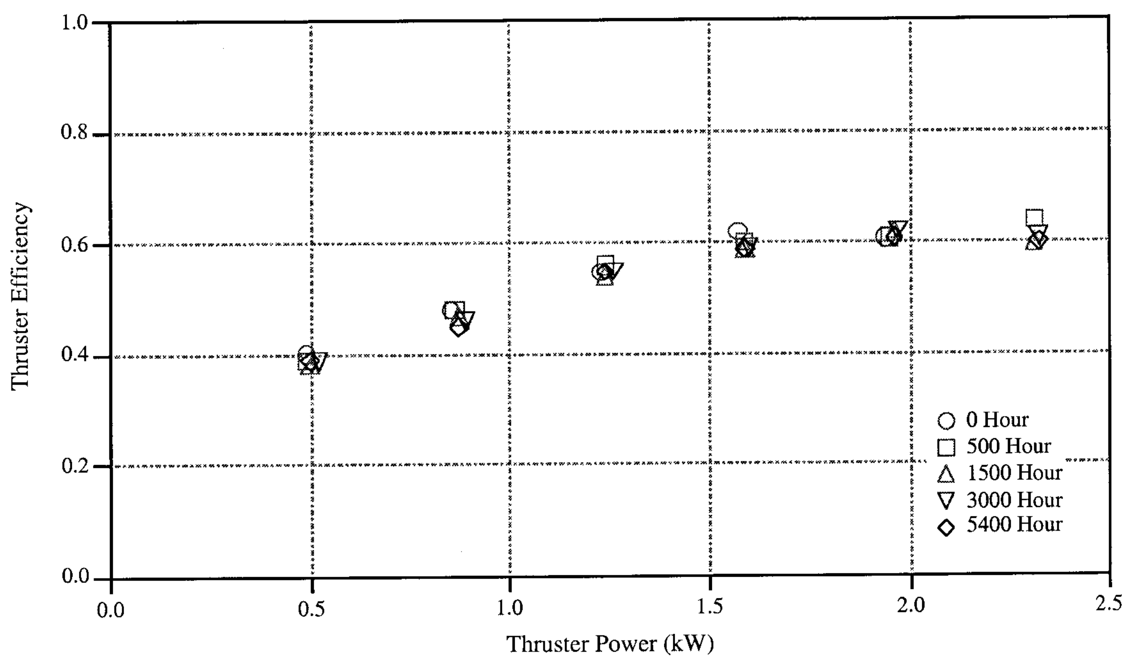

Fig. 4: FT2 Efficiency vs Power

Table 2: NSTAR Thruster Performance Data Over Throttling Range

	0 Hr	500 Hr	1500 Hr	3000 Hr	5400 Hr
Thrust (mN)					
TH0	20.3	20.1	20.0	20.0	20.2
TH3	30.4	30.7	30.4	30.5	30.0
TH6	46.0	46.8	46.0	46.1	46.3
TH9	62.5	62.1	61.6	61.6	61.5
TH12	76.6	77.1	77.5	77.1	77.0
TH15		93.7	91.2	91.6	91.2
Specific Impulse (s)					
TH0	1981	1939	1943	2013	1968
TH3	2738	2753	2736	2773	2697
TH6	3000	3039	2985	3027	3022
TH9	3166	3132	3116	3144	3116
TH12	3164	3177	3193	3211	3185
TH15		3195	3115	3146	3112
Thruster Efficiency					
TH0	0.40	0.39	0.38	0.39	0.39
TH3	0.48	0.48	0.47	0.46	0.45
TH6	0.55	0.56	0.54	0.55	0.55
TH9	0.62	0.60	0.59	0.59	0.59
TH12	0.61	0.61	0.62	0.62	0.61
TH15		0.64	0.60	0.61	0.60
Power (kW)					
TH0	0.49	0.49	0.50	0.52	0.50
TH3	0.85	0.86	0.87	0.89	0.87
TH6	1.23	1.24	1.24	1.26	1.24
TH9	1.57	1.59	1.59	1.60	1.59
TH12	1.94	1.95	1.96	1.97	1.96
TH15		2.31	2.31	2.32	2.32

the specific impulse is low because the neutralizer flow--which is not accelerated and represents a cold flow loss--is a larger fraction of the total flow rate than at power levels above 1.5 kW. The ratio of neutralizer flow to total propellant flow decreases as the power level increases resulting in higher specific impulses.

Thruster efficiency is plotted as a function of thruster power in Fig. 4. Thruster efficiency is defined as the ratio of power converted into thrust producing propellant directed kinetic energy to the total power consumed by the thruster. The efficiency decreases with decreasing power primarily because of the cold flow loss through the neutralizer. Over time the efficiency tends to decrease slightly as the power required to produce ions in the discharge chamber increases.

FT2/EMT2 Comparison

A set of plots comparing the performance of FT2 against that of EMT2 is shown in Figs. 5-18. In each of these plots the vertical dashed lines at 448 hours and at 4937 hours indicate times when the FT2 power level was changed. The TH level for FT2 during each time interval is shown on each plot; all off the EMT2 data in these plots is at full power (TH15).

Ion Optics Performance

Approximately every 50 to 200 hours a set of measurements are made to characterize the performance of the ion optics system. Three key parameters for the ion optics system are electron backstreaming limit, perveance margin and screen grid transparency to ions. As previously stated, the ion optics is used to extract and accelerate the ions produced in the discharge chamber while keeping beam neutralizing electrons from backstreaming into the discharge chamber. Electron backstreaming occurs when the potential at the center of accelerator grid apertures is insufficiently negative to prevent electrons from traveling upstream into the discharge chamber. The potential in the accelerator grid holes is dependent on a number of variables including: the electric field between the grids, the voltage applied to the accelerator grid, the ion current extracted through the aperture, and the accelerator grid aperture diameter. Electron backstreaming is most likely to occur near the center of the thruster where the maximum beam current density is extracted.

The electron backstreaming limit is determined by increasing the accelerator grid voltage until the discharge loss begins to decrease. Discharge loss is the ratio of energy cost of producing beam ions to the extracted beam current. For the beam power supply backstreaming electrons are indistinguishable from positive ions being accelerated from the discharge chamber. When backstreaming occurs the positive ion current extracted from the discharge chamber must decrease to maintain the beam current at the setpoint. As a result fewer ions must be produced in the discharge chamber and the discharge loss decreases. For the data presented here, the electron backstreaming limit is defined as the accelerator grid voltage at which the discharge loss decreases by 1%.

A comparison of electron backstreaming limit for FT2 and EMT2 is shown in Fig. 5. A large shift in the electron backstreaming limit, from -148.2 V to -139.6 V, occurred over the first 124 hours of FT2 testing. After that, the electron backstreaming is less negative at TH12 for FT2 than at TH15 for EMT2. During full power operation, the electron backstreaming for FT2 remained about 6 V more negative than that for EMT2. The long term changes in electron backstreaming limit are thought to be due primarily to accelerator grid aperture enlargement caused by ion sputtering; however, the shift during the first 124 hours of FT2 testing is thought to be due to an increase in grid spacing. An increase in the grid gap reduces the electric field between the grids, requiring a less negative accelerator grid potential to prevent electron backstreaming. It is also noted that accelerator grid aperture size would have to decrease to account for the shift which is considered unlikely.

Since thruster operation at TH8 began at 4937 hours, the electron backstreaming limit has remained essentially constant. This suggests that the accelerator grid apertures are not enlarging near the center of the grid where backstreaming is most likely to occur. This is consistent with an NSTAR project assumption that operation at lower power levels is more benign in terms of erosion of the ion optics system.

The jumps in electron backstreaming limit when power level is changed are due to differences in beam current extracted through ion optics apertures. Positive space-charge causes the potential in the accelerator grid apertures to increase as the beam current increases; therefore, a more negative accelerator grid voltage is required to prevent electron backstreaming at higher power levels where more beam current is extracted.

The 6 V difference in electron backstreaming limit between FT2 and EMT2 operating at full power is thought to be due to a slight difference in the gap between the grids. Decreasing the spacing between the grids results in a stronger intra-grid electric field. This results in a higher

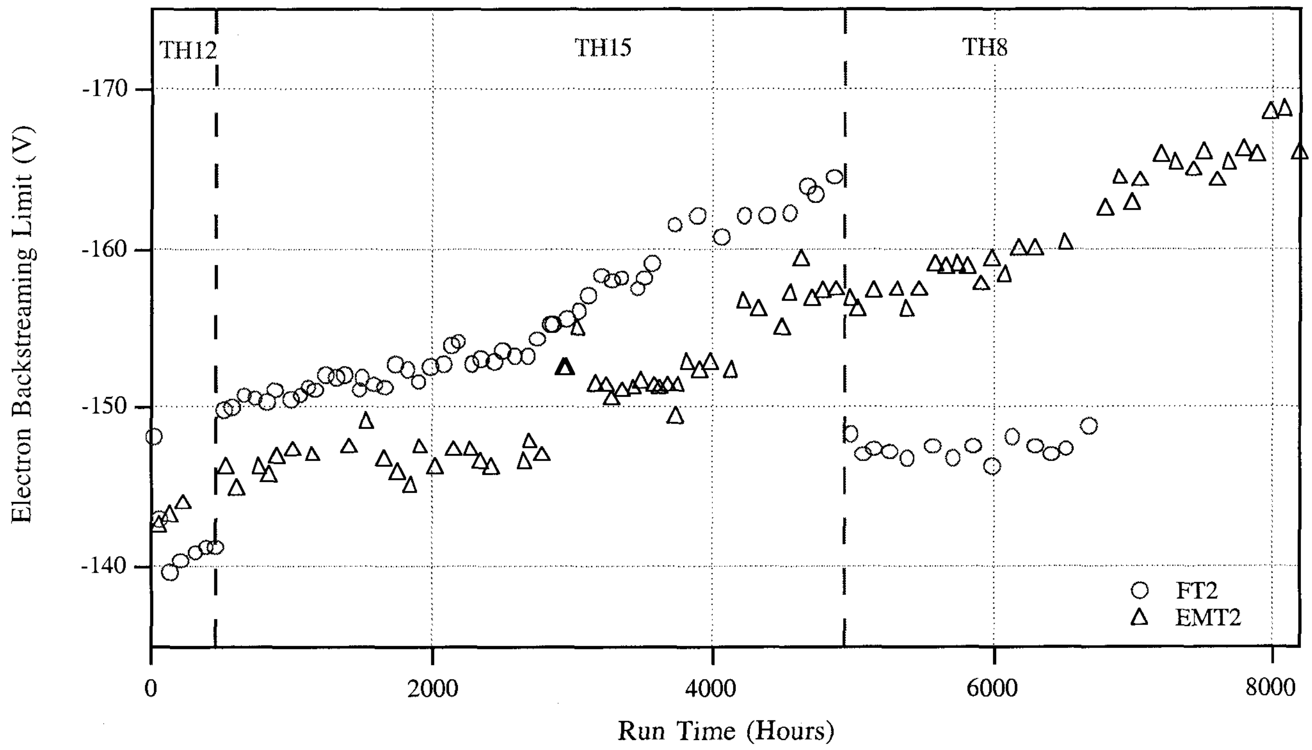

Fig. 5: Electron Backstreaming Limit Comparison for FT2 and EMT2

potential in the accelerator grid aperture, requiring a more negative accelerator grid voltage to prevent electron backstreaming. In Ref. 14 it was estimated that the 6 V lower electron backstreaming limit for FT2 could be explained if the FT2 grid spacing is 65 μm less than that for EMT2 during thruster operation. The measured pre-test grid gap for both FT2 and EMT2 was 0.58 mm. These measurements were made with the grids at ambient temperature. The grid spacing is expected to change as the grids warm up during thruster operation.

The electron backstreaming limit is an important parameter because of its effect on thruster lifetime. Thruster failure occurs when the electron backstreaming limit exceeds the voltage capability of the accelerator grid supply, for DS1 this is -250 V. The rate at which the electron backstreaming limit changes is dependent on the aperture erosion rate which increases as the energy of the impinging ions increases. Since this energy depends on the magnitude of the accelerator grid voltage, it is desirable to minimize this magnitude.

In addition to electron backstreaming measurements, perveance measurements are made to determine the margin from direct ion impingement at normal operating conditions. Rapid accelerator grid erosion occurs when energetic ions impinge on the grid surface. Care must be taken to avoid accelerating ions from the discharge chamber directly onto the accelerator grid surface during normal thruster operation. Direct ion impingement for a prolonged period can cause severe accelerator grid erosion because these ions are accelerated through the total voltage applied between the grids.

The perveance limit is measured by defocusing the ion beam until ions directly impinge on the accelerator grid. Defocusing is accomplished by reducing the screen grid voltage. For the data presented here, the perveance limit is defined as the screen grid voltage at which a 0.02 mA increase in accelerator grid current is caused by a 1 V decrease in screen grid potential. Perveance margin is the difference between the screen grid voltage and the perveance limit.

A comparison of the perveance margin data for FT2 and EMT2 is shown in Fig. 6. The perveance margin at TH12 for FT2 is higher than that at TH15 for EMT2. This occurs because the beam current is lower at TH12 than at TH15 and the beamlets must defocus more before they impinge on the accelerator grid. When operating FT2 at TH15, the perveance margin initially was worse (lower) than that observed during EMT2 testing. However, by 2500 hours the perveance margins for both thrusters were comparable. Over the first 1000 hours, the perveance margin increased rapidly for both thrusters, after which it settled out to a nearly linear rate of increase. This occurs because as the accelerator grid holes enlarge with time, due to ion sputtering, the beamlets must become more

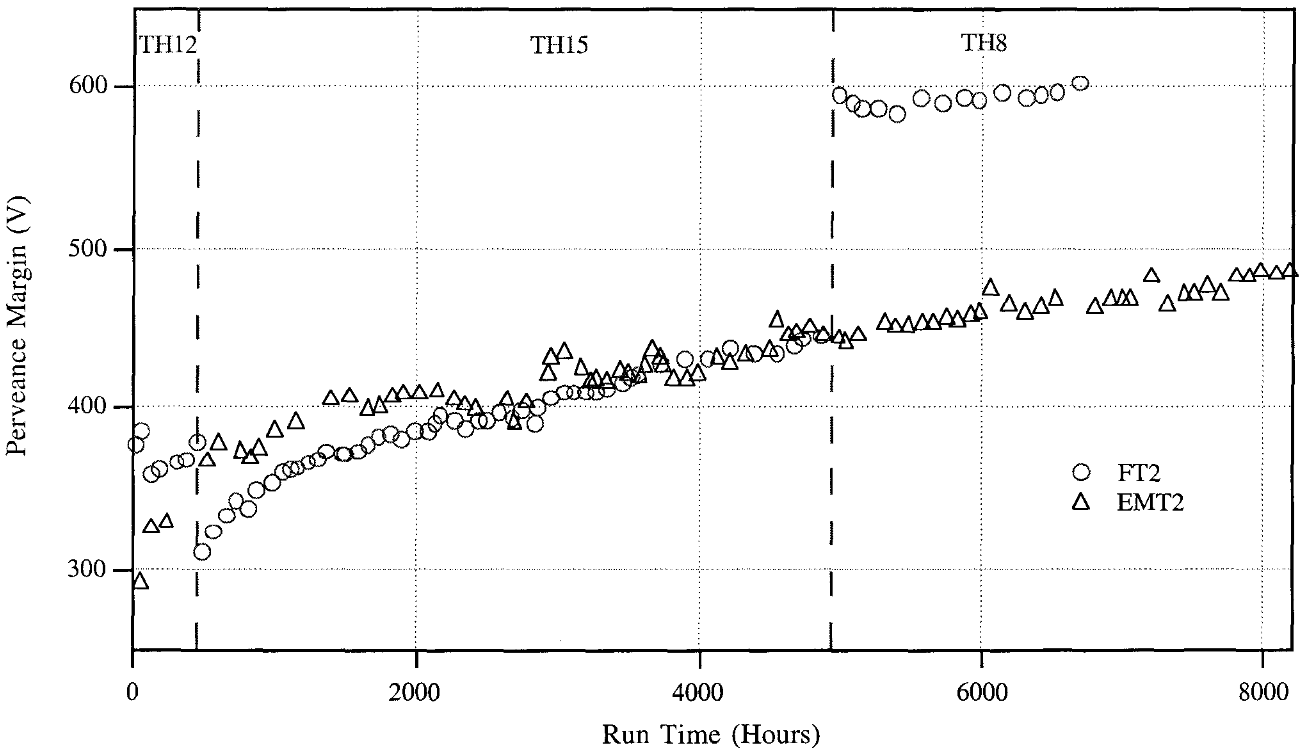

Fig. 6: Perveance Margin Comparison for FT2 and EMT2

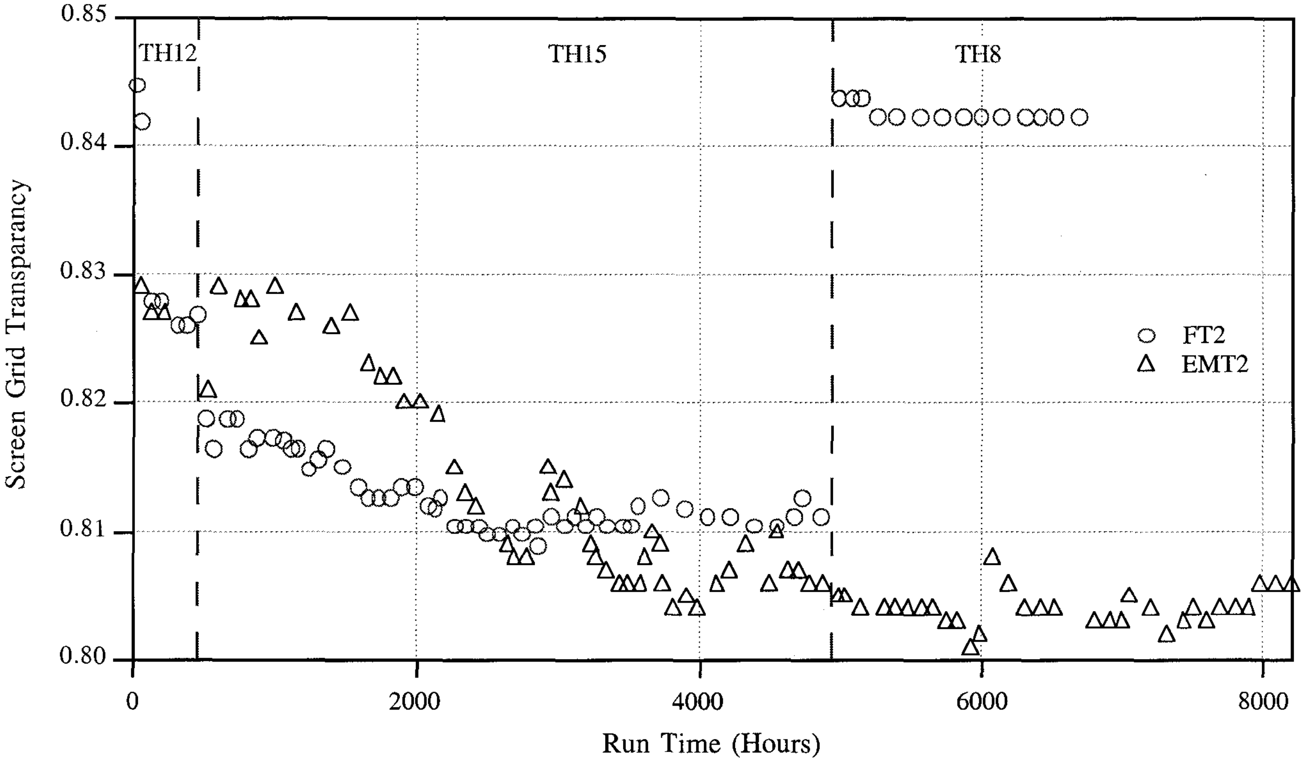

Fig. 7: Screen Grid Transparency Comparison for FT2 and EMT2

defocused to impinge on the accelerator grid. The shift prior to 124 hours is also noted in the perveance margin data for FT2.

After throttling to TH8 the perveance margin is larger because less beam current is extracted from the thruster and the beamlets are further from the edges of the accelerator grid apertures. It is also noted that the perveance margin has remained relatively constant during FT2 operation at TH8. This is another indicator that accelerator grid aperture erosion is lower at TH8 than at TH15.

Screen grid transparency to ions is a measure of how effectively the optics extract ions from the discharge chamber. Screen grid transparency to ions is measured by biasing the screen grid 20 V negative with respect to cathode potential. This keeps discharge chamber electrons from being collected on the screen grid. The screen grid transparency is defined as the ratio of the ion current extracted through the screen grid to the total ion current directed toward the screen grid. The total ion current directed toward the grid is the sum of the current extracted through the grid and the current that impinges on the screen grid.

A plot comparing screen grid transparency for FT2 and EMT2 is shown in Fig. 7. The shift over the first 124 hours of FT2 testing is also noted in the transparency data. After this initial shift in screen grid transparency, the transparency measured at TH12 on FT2 and at TH15 during EMT2 testing were comparable. At full power the FT2 screen transparency was less than that of EMT2 up to about 2500 hours. After about 3000 hours, the screen grid transparency for FT2 at full power was slightly higher than that for EMT2. The reason for these differences at full power is not known; however, they may be due to small differences in grid spacing between the two thrusters. After throttling to TH8 the transparency has been higher than that observed at TH15 or TH12 after the shift during the first 124 hours of FT2 testing. The transparency has remained relatively constant during operation at TH8, which is yet more evidence that erosion of the ion optics system is low at this operating point. Although the observed transparency differences are relatively small, they do affect discharge chamber performance; more ions must be produced to provide the desired beam current if the transparency is smaller.

Discharge Chamber Performance

Shown in Figs. 8 and 9 are the cathode and main flow rates, respectively. At full power the FT2 cathode flow rate is 2.7% less and the main flow rate is 1.9% lower than in EMT2 testing. The FT2 test plan called for the flow rates to be the same as those during EMT2 testing. However, a calibration error which was not discovered until 3780 hours resulted in the FT2 flows being lower than the EMT2

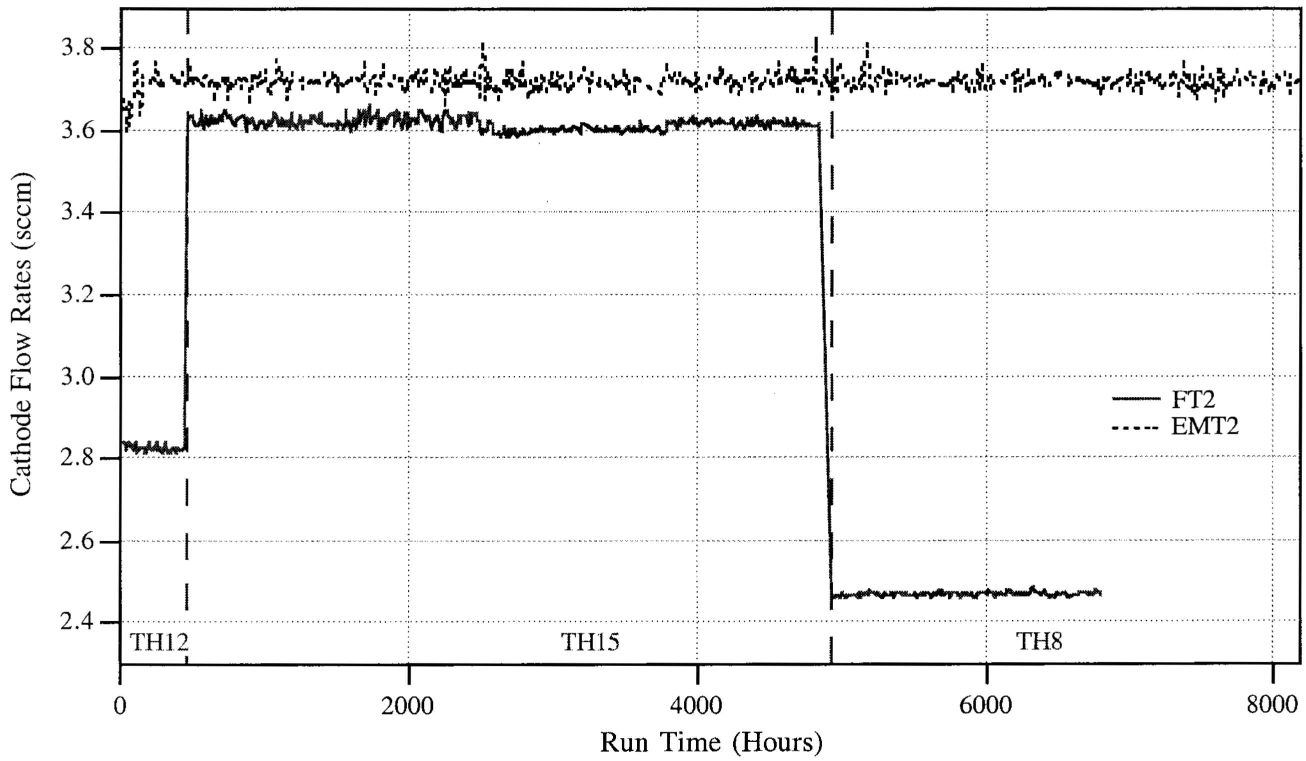

Fig. 8: Cathode Flow Rate Comparison for FT2 and EMT2

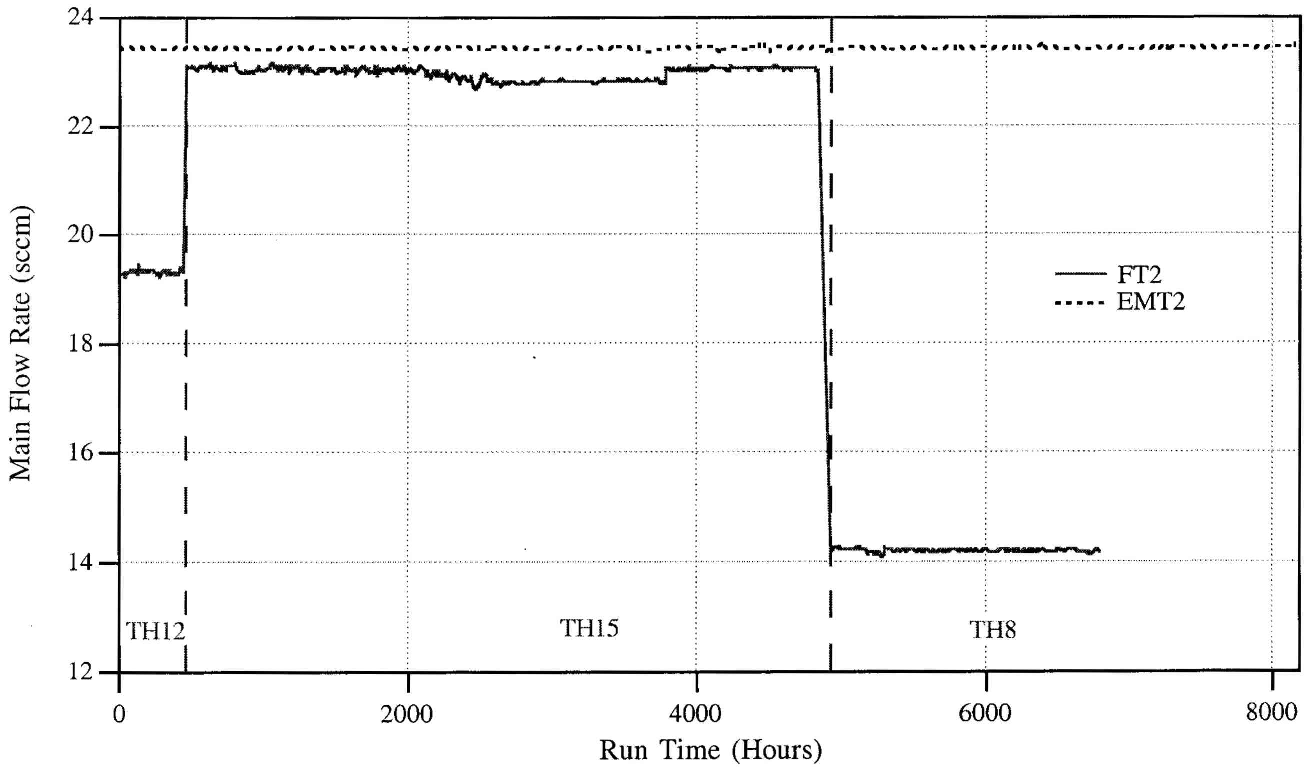

Fig. 9: Main Flow Rate Comparison for FT2 and EMT2

flows by the amounts indicated above. The main flow controller drifted an additional 1% lower between 2000 and 2350 hours. The flow meters were recalibrated at 2350 hours; however, the calibration error was dependent on the ambient temperature which was different for the previous calibration. The error introduced by the temperature difference coincided with the drift in the main flow meter, so the main flow rate remained the additional 1% low until the calibration error was discovered. The lower flow rates do not appear to have a deleterious effect on FT2. Because the lower flow rates results in less cold flow propellant loss, FT2 operation at the lower flow rates was continued after the calibration error was discovered.

The discharge current for both FT2 and EMT2 is shown in Fig. 10. The discharge current at TH12 and TH8 during FT2 testing are lower than that at TH15 because fewer ions are required to provide the smaller beam currents extracted from the thruster at lower power levels. The initial 2974 hours of EMT2 testing were conducted using a breadboard PPU. The breadboard PPU discharge power supply was limited to 13.5 A until 2100 hours when it was modified to allow operation at higher discharge currents. After throttling FT2 to full power, the discharge current was about 0.5 A higher than that for EMT2 and the rate of increase was lower. The FT2 discharge current remained higher up to 3000 hours when the EMT2 current surpassed that of FT2. These trends are similar to the trends in screen grid transparency. In Ref. 14, a strong correlation between $1-f_s$ (where f_s is the screen grid transparency) and discharge current was noted. The factor $1-f_s$ represents the fraction of discharge chamber ions directed toward the ion optics which strike the screen grid. Because more ions must be produced to make up for the ions lost to the screen grid some sensitivity of the discharge current to this loss is anticipated; however, the sensitivity is much stronger than a $1/f_s$ dependence suggested by a preliminary analysis using the discharge chamber performance model developed by Brophy [12]. The observed correlation may be due to ion optics erosion. As the accelerator grid apertures erode, the area through which neutral propellant can escape from the discharge chamber increases. As a result the neutral density in the discharge chamber decreases and a higher discharge current is needed to produce the ions required for the beam current. In addition, material sputtered from the accelerator grid can redeposit on the screen grid reducing the screen grid aperture area; this results in a decrease in screen grid transparency. The combined effect of increasing accelerator grid aperture size and decreasing screen grid aperture size may account for the observed correlation. More work to adequately modeled the observed correlation is needed.

Since throttling to TH8, the FT2 discharge current has been decreasing. The reason for this decrease is not known; however, the discharge voltage, shown in Fig. 11, is higher for FT2 than EMT2 while FT2 was operating at the

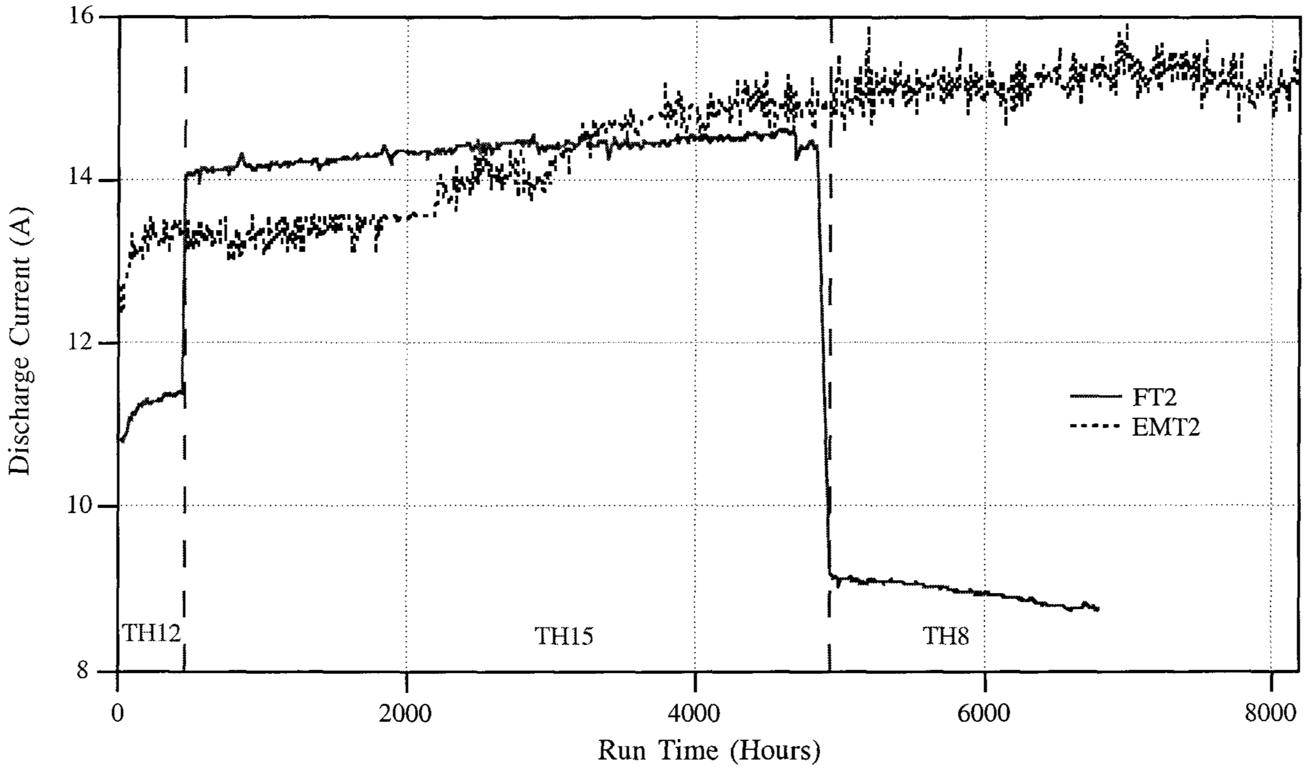

Fig. 10: Discharge Current Comparison for FT2 and EMT2

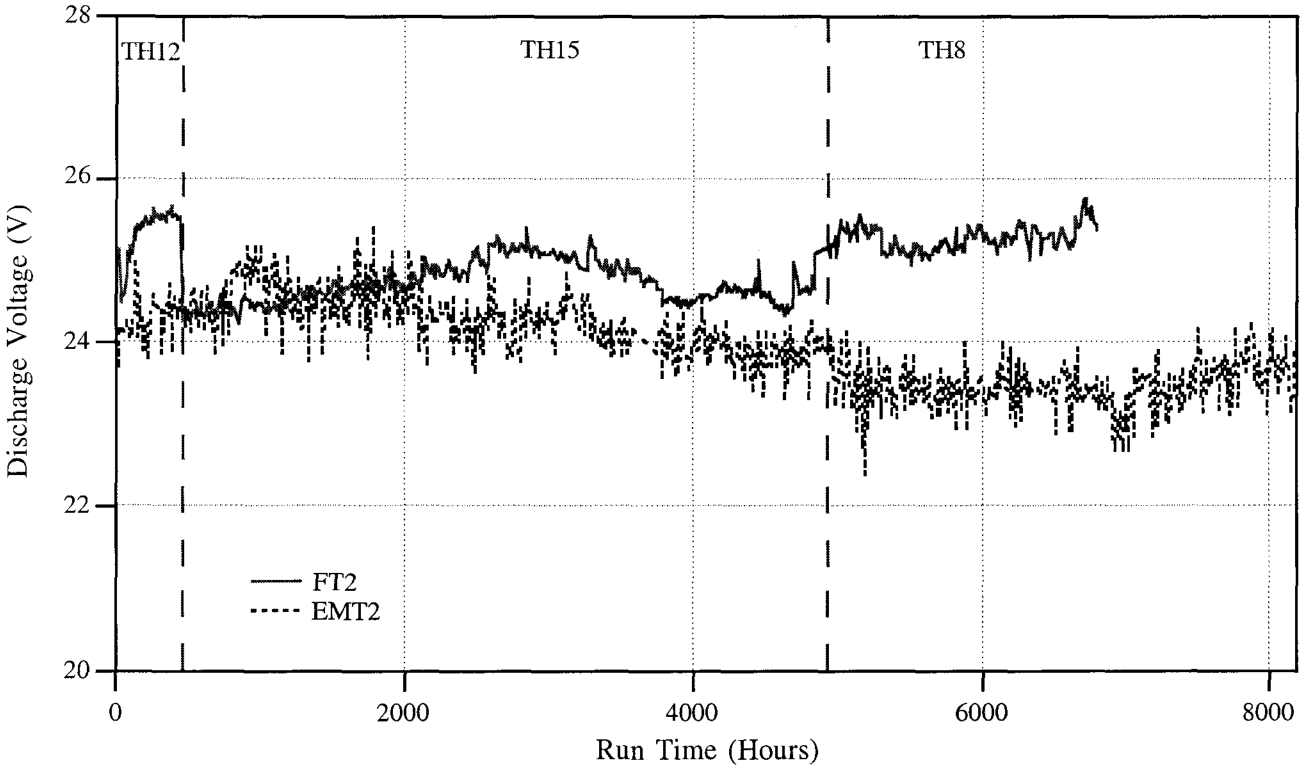

Fig. 11: Discharge Voltage Comparison for FT2 and EMT2

lower power levels. The voltages were roughly equal at full power until about 2000 hours. After 2000 hours the FT2 discharge voltage was about 0.5 V higher than EMT2 during full power operation. The discharge voltage for FT2 at TH8 is about 2 V higher than that of EMT2 operating at TH15.

A comparison of the discharge loss for EMT2 and FT2 is shown in Fig. 12. It is seen that the discharge loss for FT2 is higher by about 12 eV/ion than that for EMT2 until the discharge current became lower for FT2 than EMT2 at 3000 hours; after that the discharge loss for FT2 decreased as the discharge voltage decreased. After 4000 hours the discharge loss for both thrusters, operating at full power, coincide even though the discharge currents and discharge voltages are slightly different for the two thrusters. After throttling FT2 to TH8, the discharge loss increased about 8 eV/ion and then slowly decreased back to a level comparable to that observed during operation at full power.

The double-to-single ion current ratio is shown in Fig. 13 for FT2 and EMT2. Initial pointing of the ExB probe during FT2 testing was done before the shift occurred in the ion optics performance parameters over the first 124 hours of the test. The probe was aligned so that the single ion current to the probe was maximized. The shift in the ion optics may have caused a change in the direction at which the ExB probe received the maximum single ion current, resulting in low measured double ion ratio. The probe was operated with the initial pointing until 607 hours, when the probe was realigned to receive the maximum single ion current. With this pointing, the double-to-single ion ratio for FT2 was found to be comparable to but slightly less than that of EMT2 at full power. The difference is thought to be due to slight alignment variations of the probe between the two tests. Another factor which could contribute to the difference is that the probe used in the EMT2 test accepted ions from a 3.1 cm wide strip across the thruster diameter while the probe used in FT2 testing accepts ions over a 1.8 cm wide strip across the thruster diameter. The difference in width of the acceptance area may affect the observed double-to-single ion ratio if doubles are preferentially produced near the thruster centerline. After reducing the FT2 power level to TH8, the double-to-single ion ratio has remained relatively constant at a lower level than that observed at full power. This occurs because the plasma density is lower in the discharge chamber at lower power levels. Most of the doubly ionized propellant is produced by electron collisions with singly ionized xenon; because the single ion density is smaller at lower power levels, fewer double ions are produced as the power level decreases.

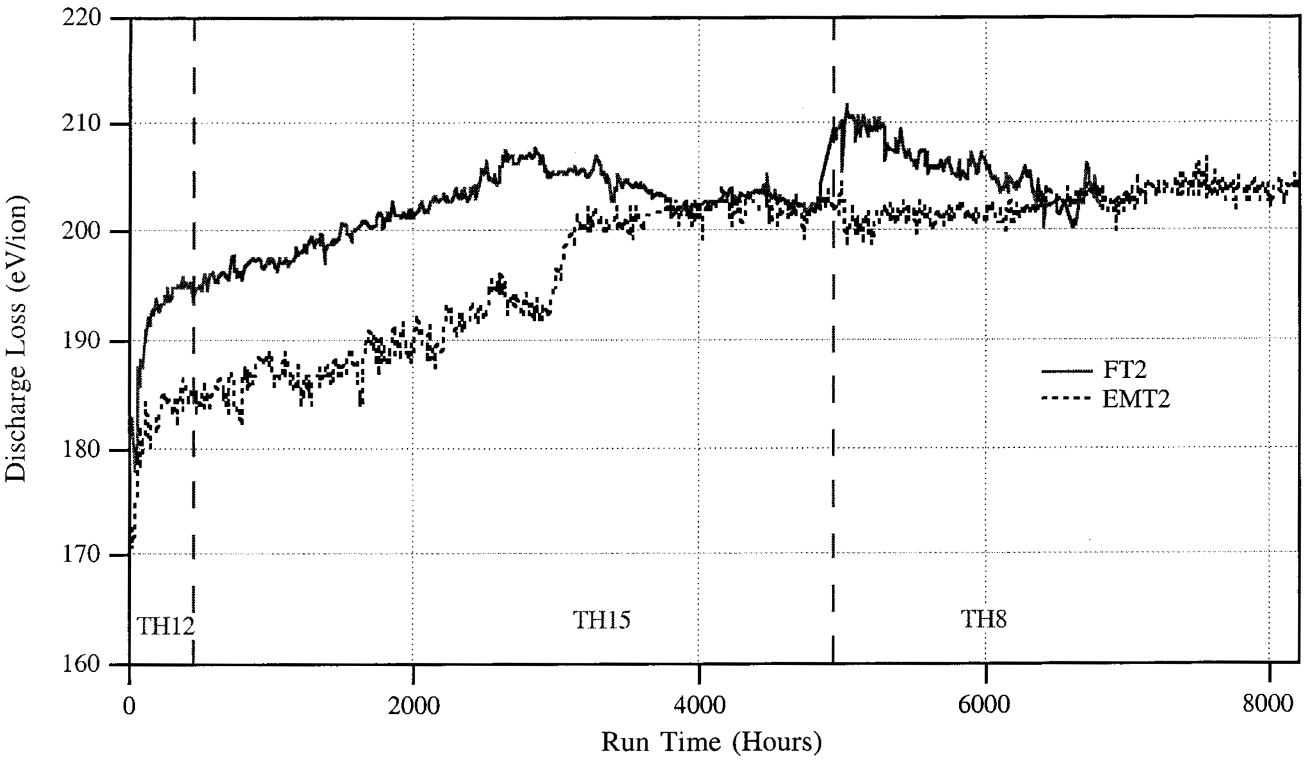

Fig. 12: Discharge Loss Comparison for FT2 and EMT2

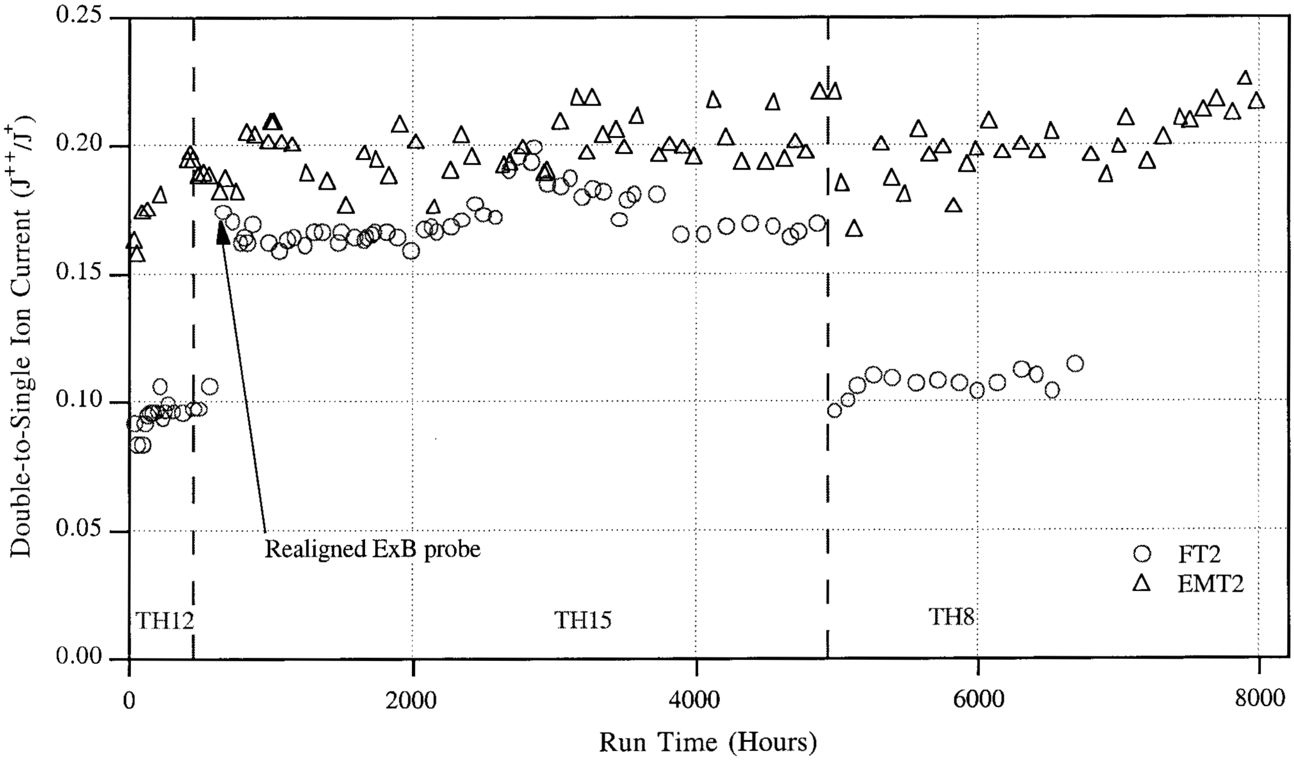

Fig. 13: Double Ion Ratio Comparison for FT2 and EMT2

Neutralizer Performance

The neutralizer is used to provide neutralizing electrons to the ion beam. To keep the neutralizer from extinguishing during recycles, a keeper electrode and a current regulated power supply are used to maintain the current levels specified in the throttle table. The neutralizer keeper voltage is affected by the keeper current and the neutralizer flow rate.

The neutralizer flow rate for FT2 and EMT2 are shown in Fig. 14. At the start of the EMT2 test, the full power neutralizer flow rate was set at 3.0 sccm. Although there was enough margin to avoid plume mode operation at full power, the neutralizer flow rate was increased when the DS1 xenon flow system was designed so that the discharge cathode and neutralizer flow rates were nearly matched [15, 16]. The higher neutralizer flow rates used in the DS1 flow system are also being for FT2.

The neutralizer keeper voltages for FT2 and EMT2 are shown in Fig. 15. The keeper voltage for FT2 is generally lower than that for EMT2. The spikes in the keeper voltage for both tests correspond to situations where the cathodes were conditioned after cryopump regeneration. The lower keeper voltage on FT2 during full power operation is accounted for by the higher flow rate. After throttling FT2 to TH8, the neutralizer keeper voltage is higher than that of EMT2 operating at full power. The keeper voltage is also an indicator of how near the neutralizer is to plume mode with higher keeper voltage indicating there is less margin to avoid plume mode.

Thrust Magnitude and Direction

Shown in Fig. 16 is a comparison of the thrust calculated from electrical thruster parameters for FT2 and EMT2 and thrust measurements made during FT2 testing. The calculated thrust is based on the measured beam current and voltage, a constant value of 0.98 for the beam divergence correction and a correction for multiply charged ions based on a curve fit to centerline double ion current measurements as a function of propellant utilization efficiency in a 30 cm, ring-cusp inert gas thruster [17]. The uncertainty in the calculated values is on the order of ±2.1 percent. The thrust measurements for FT2 agree with the calculated thrust within the measurement uncertainty of ±2.5 %.

Shown in Figs. 17 and 18 are comparisons of the vertical and horizontal thrust vector angles, respectively, for FT2 and EMT2. Transients of about 0.2° over the first 1500 hours are observed in the horizontal angle for both thrusters. A transient of about 0.2° lasting about 1000 hours is seen in the vertical angle for FT2. A short term

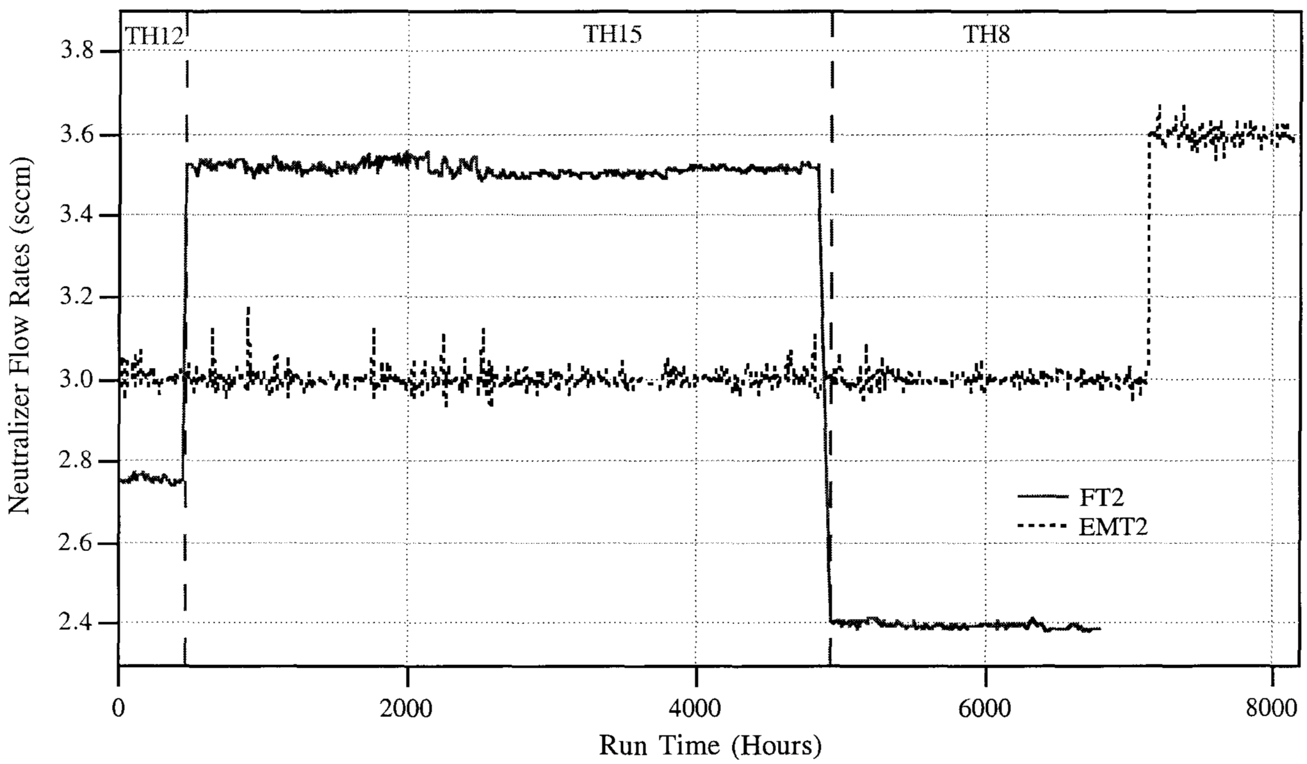

Fig. 14: Neutralizer Flow Comparison for FT2 and EMT2

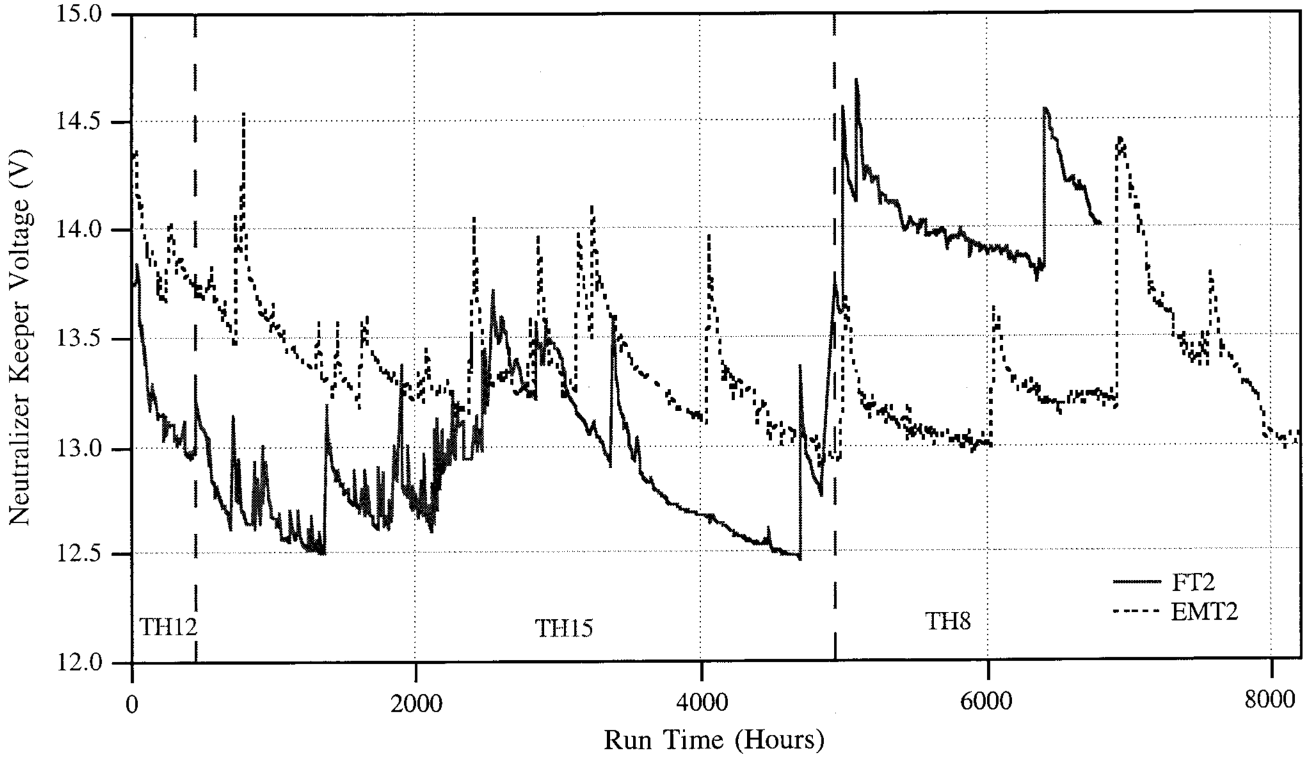

Fig. 15: Neutralizer Keeper Voltage Comparison for FT2 and EMT2

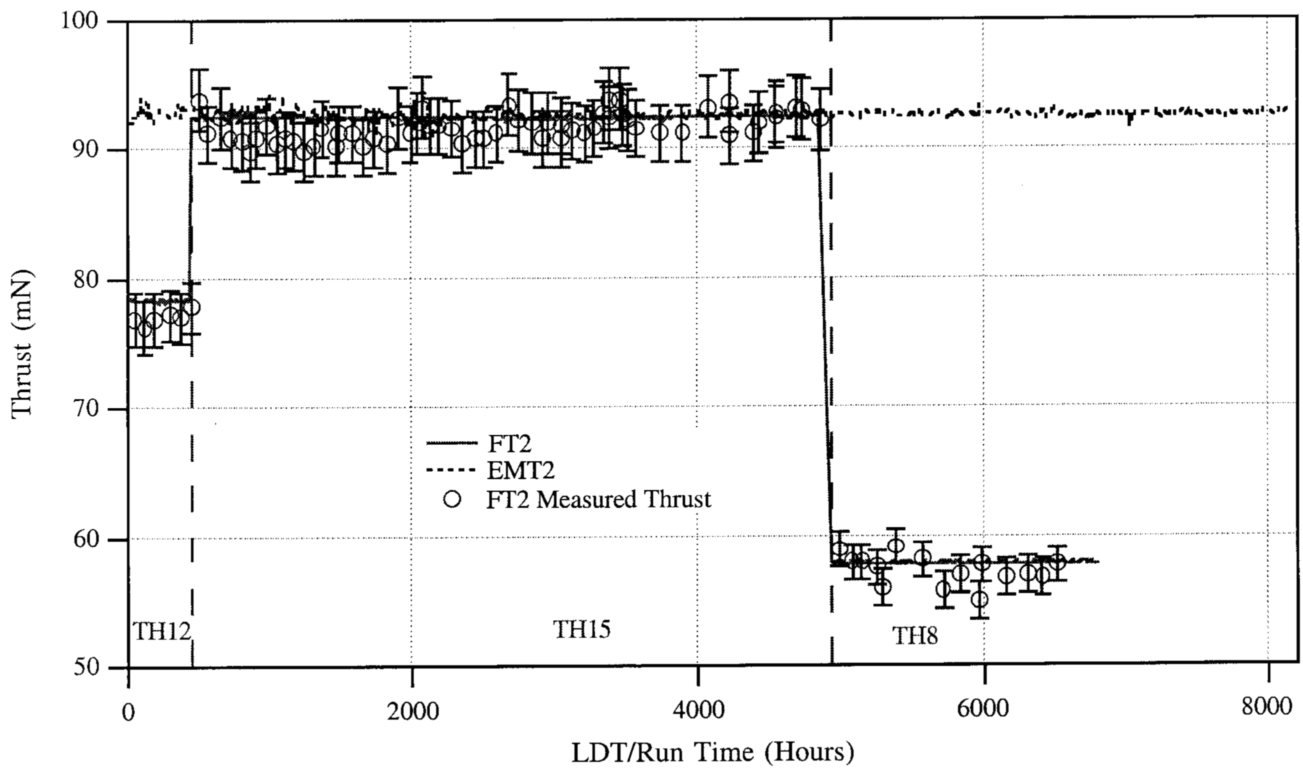

Fig. 16: Thrust Comparison for FT2 and EMT2

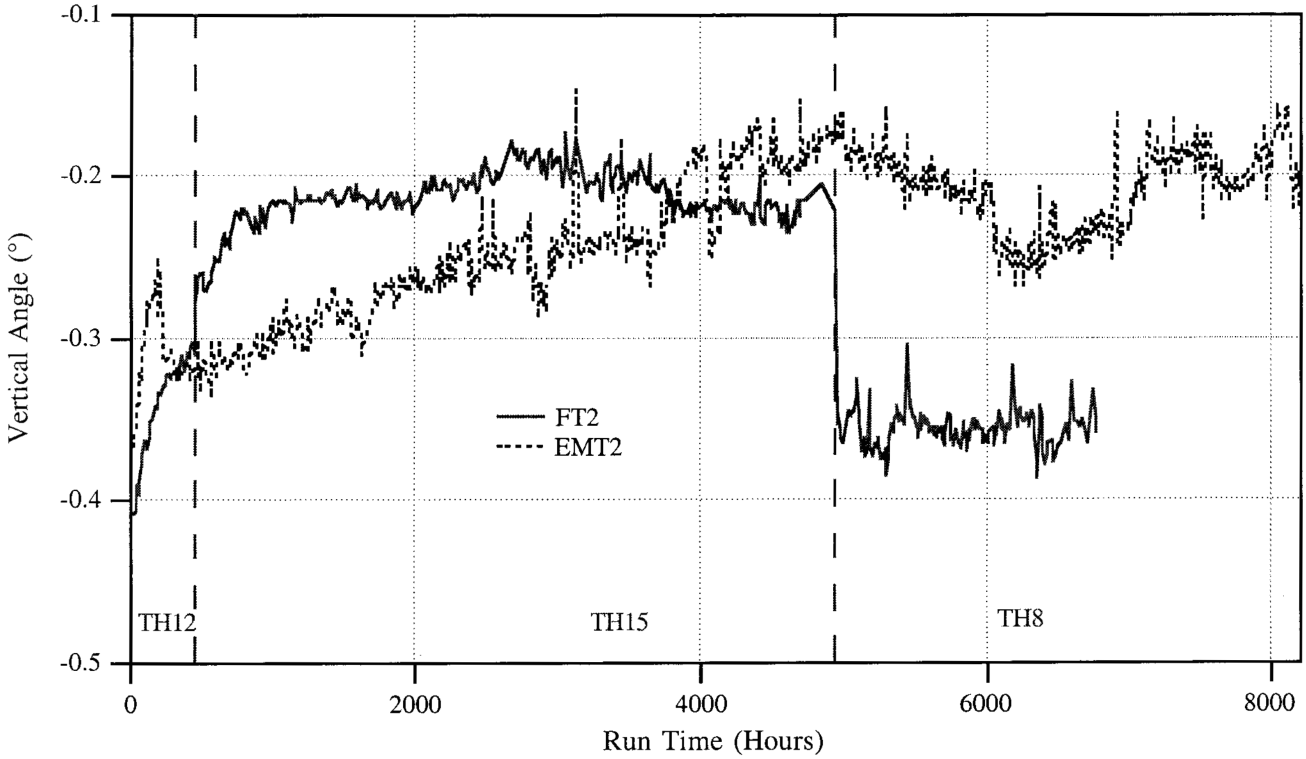

Fig. 17: Vertical Thrust Angle Comparison for FT2 and EMT2

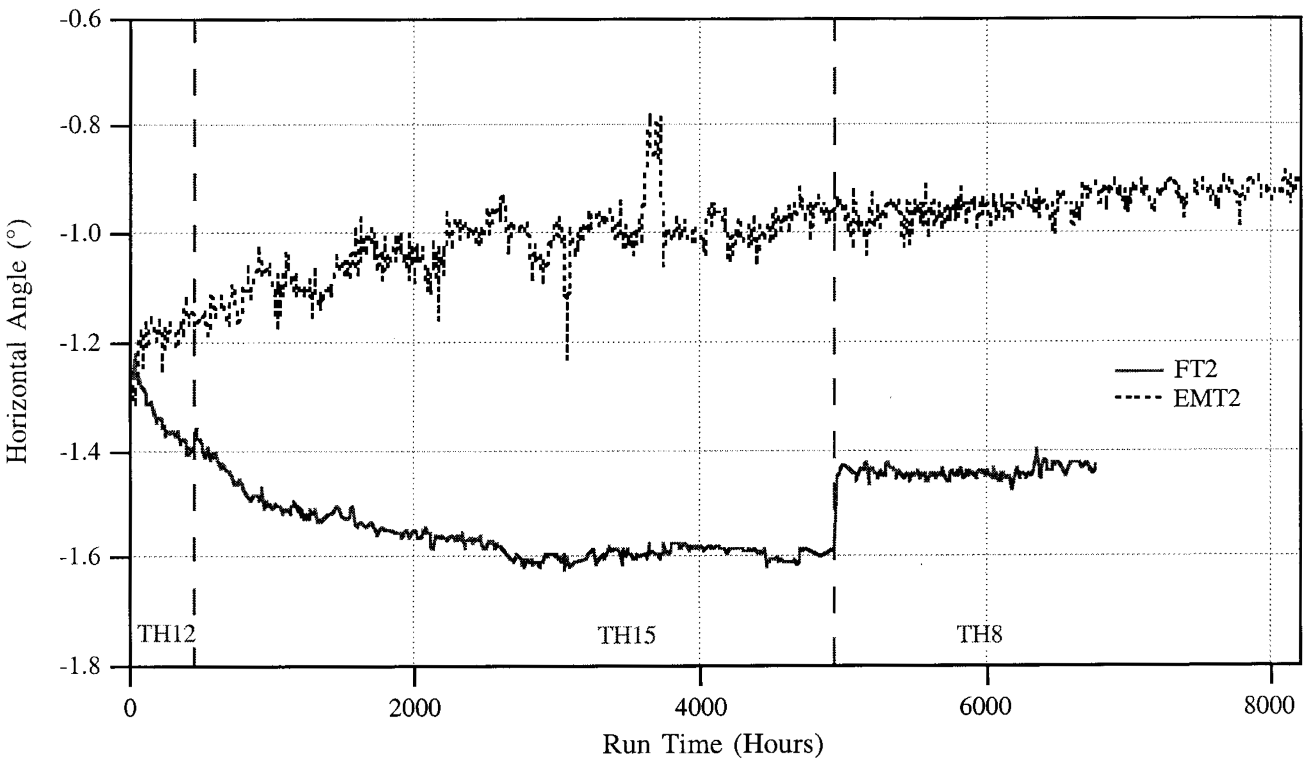

Fig. 18: Horizontal Thrust Angle Comparison for FT2 and EMT2

transient of about 0.1° over about 500 hours followed by a long term drift of about 0.1° variations is observed in the EMT2 data. A shift of about 0.15° is observed in both the horizontal and vertical angles when FT2 was throttled from TH15 to TH8. These changes in thrust vector are small; a typical spacecraft gimbal system, with a range of several degrees, can easily compensate for the observed variations.

Neutralizer and Cathode Electrical Isolation

Another generic failure mode for ion thrusters is loss of electrical isolation between components. Degradation in the electrical isolation for neutralizer and discharge cathode components has been observed during this test. The electrical isolation between components is measured using a digital ohm meter and is also measured using a Hypot. The portable DC Hypot (manufactured by Associated Research, Inc.) is a high voltage (up to 15 kV) low current (2 mA maximum) power supply used to measure electrical impedance between components with high voltage applied across them. Hypot impedance tests conducted on neutralizer and discharge cathode components of FT2 are done at 1000 V.

Degradation of neutralizer keeper-to-neutralizer common impedance, as well as the impedance of both components to facility ground, has been observed during FT2 testing. It is possible to operate the thruster if either the neutralizer keeper or neutralizer common is shorted to facility ground (or spacecraft ground in flight); however, the thruster would no longer be decoupled from ground. Degradation of neutralizer keeper-neutralizer common impedance, if severe enough, can cause thruster failure. The impedance level where neutralizer failure occurs is somewhere between 10 and 1 Ω. Depending on the power level at which the thruster is operating, the neutralizer keeper collects either 1.5 or 2.0 A. Typically the neutralizer keeper voltage is between 12 and 15 V as shown in Fig. 15. If the neutralizer keeper-neutralizer common impedance were 1 Ω, most of the neutralizer keeper current would flow through the low impedance leakage path and it would be impossible to maintain the neutralizer discharge. At 10 Ω impedance roughly a tenth of the neutralizer keeper current would flow through the leakage path. Although this would reduce the margin from plume mode operation, the neutralizer would probably function well enough to allow thruster operation.

The impedance between neutralizer keeper and facility ground is shown in Fig. 19. The horizontal dashed line at 40 MΩ represents the largest resistance the digital ohm meter is capable of measuring. As measured by the Hypot, the isolation between neutralizer keeper and facility ground was over 10 GΩ before the FT2 test was started. The impedance decreased to about 40 MΩ after 448 hours of thruster operation. Digital ohm meter readings were taken in addition to the Hypot readings. Digital ohm meter readings that exceed 40 MΩ are shown as solid circles at 40 MΩ on the plot. Between 448 hours and 3200 hours the neutralizer keeper-facility ground isolation decreased to

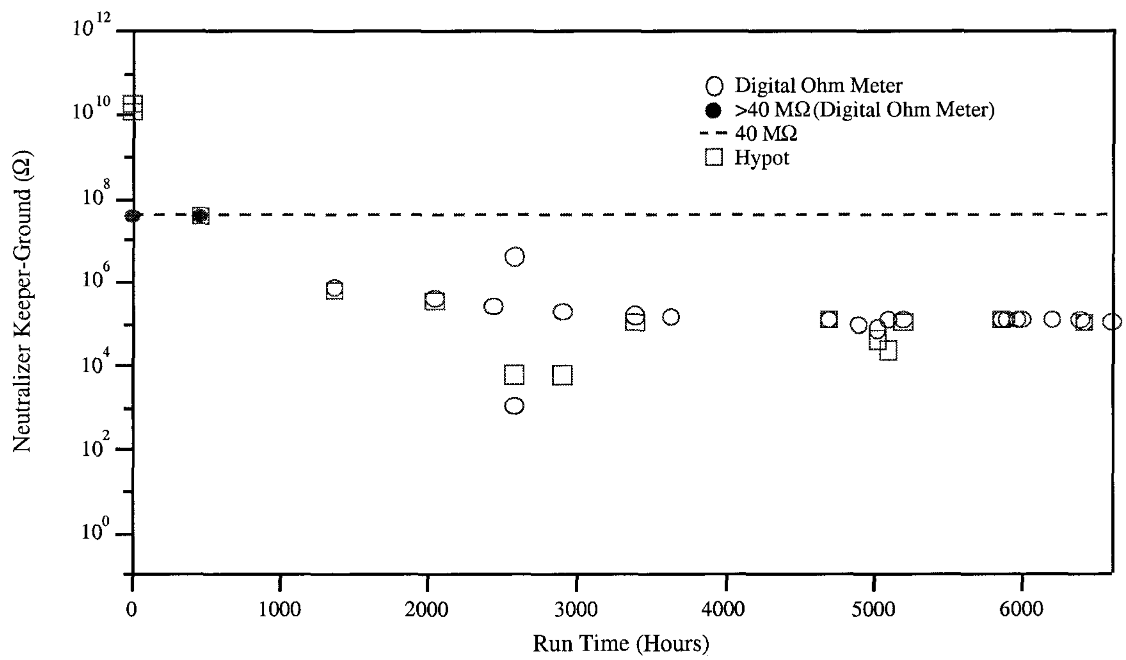

Fig. 19: Neutralizer Keeper-to-Facility Ground Impedance

about 100 kΩ and has remained relatively constant at this value.

The cause of the degradation in the neutralizer keeper-facility ground impedance will not be determined until the neutralizer can be inspected after completion of the FT2 test. However, possible causes for the observed decrease in electrical isolation include degradation of wiring insulation and deposition of a conductive coating on ceramic insulators. Decreased impedance could also be caused by thin films of carbon—backsputtered onto the thruster from the graphite panels which line the interior of the vacuum facility—spalling and bridging the gap between neutralizer keeper and facility ground surfaces. It is thought that the electrostatic force produced by the Hypot voltage caused such films or flakes of conducting material to move and bridge the gap between neutralizer keeper and facility ground during the two Hypot measurements taken between 2500 and 3000 hours. The impedance measured with the digital ohm meter prior to these Hypot measurements was in the 100 kΩ range. During the Hypot measurements, the impedance decreased to the 1 kΩ range. The material causing the decreased impedance apparently cleared during subsequent thruster operation and the impedance has remained at about 100 kΩ.

During normal thruster operation the neutralizer keeper couples through the plasma to the ground potential vacuum facility walls; as a result neutralizer keeper voltage is within 5 V of facility ground. The leakage current through the ~100 kΩ neutralizer keeper-facility ground impedance is on the order of 50 μA. The power consumed in this impedance is about 0.25 mW which does not significantly impact thruster performance.

Neutralizer common-to-facility ground impedance is shown in Fig. 20. Prior to the start of the test this impedance was greater than 1 GΩ. The electrical isolation decayed over the first 3200 hours of the test to about 10 MΩ and it has remained at this value since then. Possible causes for the reduction in neutralizer common-facility ground impedance include deterioration of wiring insulation and degradation of the neutralizer propellant flow isolator.

The impedance between neutralizer keeper and neutralizer common is shown in Fig. 21. Here the impedance measured with the digital ohm meter includes two leakage paths in parallel. One path is between the components independent of ground. The other includes the leakage path of each component to ground which are in series. The Hypot has three leads and the impedance between the components can be measured while the current to ground is shunted around the Hypot ammeter. The neutralizer common-facility ground impedance dominates the series path going through ground. In addition, the series path has a smaller impedance than the path independent of ground; therefore, the digital ohm meter readings are similar to those between neutralizer common and facility ground. The Hypot readings show that the impedance in the path independent of ground decreased during the first 2000 hours of the test and then jumped back up to the GΩ range until about 5000 hours at which point it decreased to the MΩ

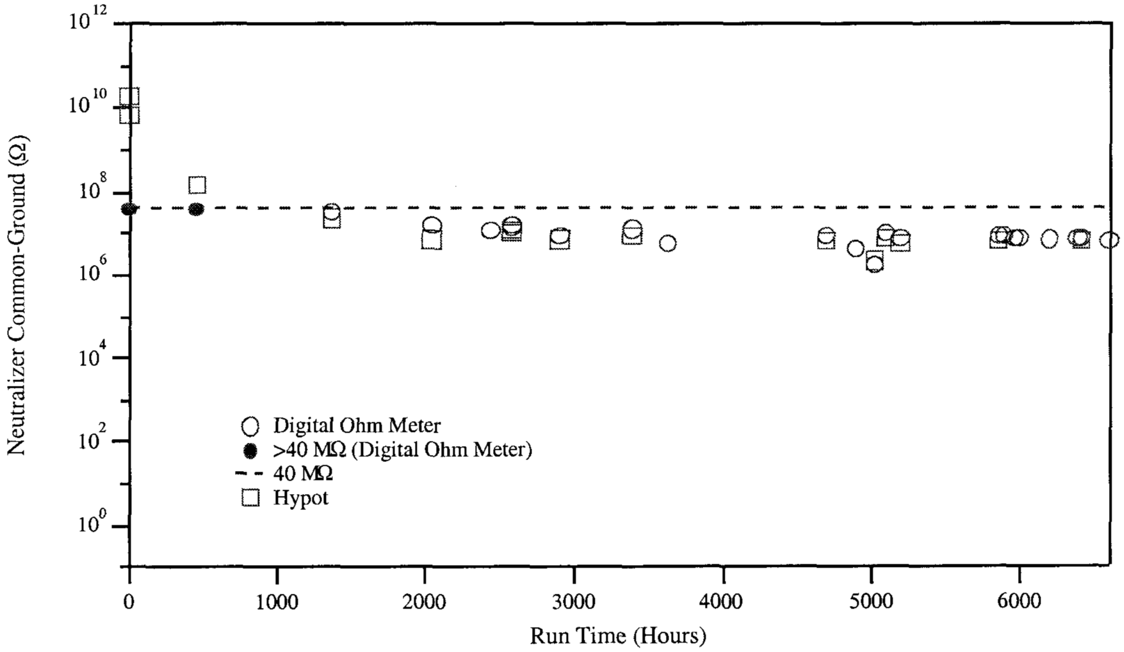

Fig. 20: Neutralizer Common-to-Facility Ground Impedance

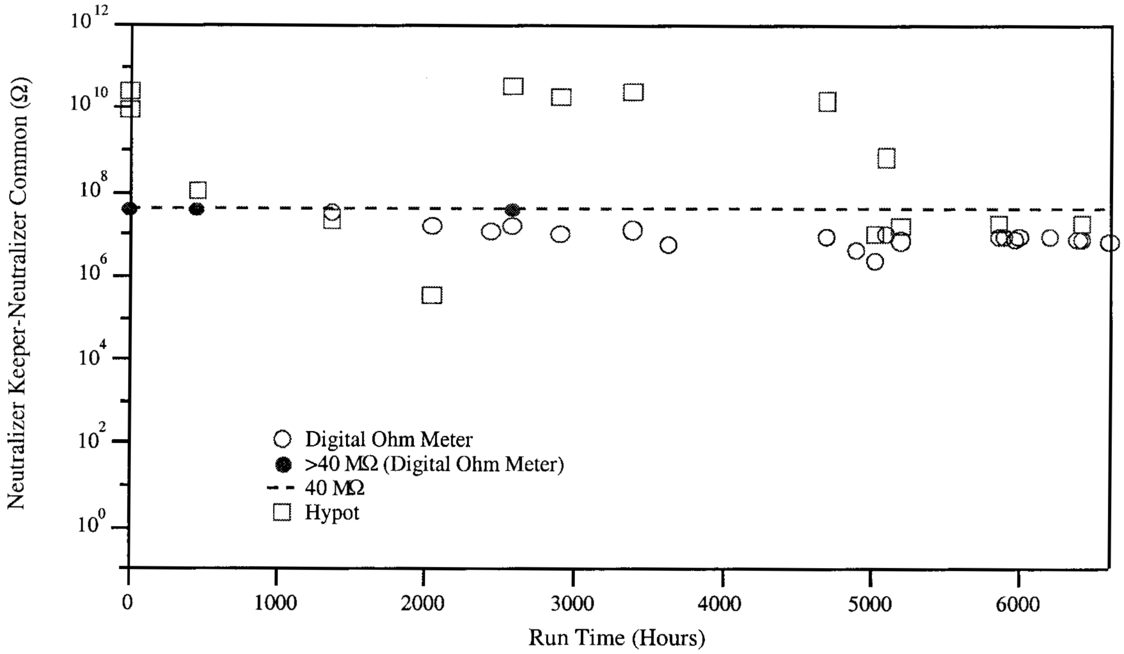

Fig. 21: Neutralizer Keeper-to-Neutralizer Common Impedance

range. At the MΩ level observed in the test, the leakage currents are on the μA level and do not significantly impact the neutralizer operation. Possible causes for the reduction in neutralizer keeper-neutralizer common impedance include neutralizer heater radiation shielding contacting the neutralizer keeper and a conducting layer depositing on the ceramic used to isolate neutralizer keeper from neutralizer common.

Degradation of discharge cathode common-to-cathode keeper impedance and discharge cathode common-to-anode isolation has been observed during FT2 testing. It is possible to operate the discharge chamber if cathode keeper is shorted to cathode common. The cathode keeper, tied to anode through a 1 kΩ resistor, is in close proximity to the cathode and is used to start the discharge. If cathode keeper is shorted to cathode common, the discharge must be started to the anode which is physically further away from the cathode than the cathode keeper; this makes starting the discharge more difficult. Degradation of cathode common-anode impedance, if severe enough, can cause thruster failure. The impedance level where cathode failure occurs is somewhere between 10 and 1 Ω. Depending on the power level at which the thruster is operating, the discharge current between the discharge cathode and anode can vary between 4 and 16 A and the discharge voltage is usually between 24 and 29 V. If the cathode common-anode impedance were 1 Ω, most of the discharge current would flow through the low impedance leakage path and it would be impossible to operate the discharge chamber. At 10 Ω impedance over 2 A would flow through the leakage path. Although it might be possible to operate the thruster with such a loss, discharge chamber performance would be seriously degraded.

Discharge cathode common-anode impedance is shown in Fig. 22. For the first 2000 hours the impedance was greater than 10 GΩ. At about 2000 hours the impedance decreased to the MΩ range where it has remained relatively constant since. Possible causes for the reduction in cathode common-anode impedance include a conducting layer depositing on the ceramic used to isolate cathode common from anode or a conductive path between pins in the thruster wiring cable connector.

Discharge cathode keeper to discharge cathode common impedance is shown in Fig. 23. The impedance was greater than 1 GΩ up until 6408 hours. At that point the digital ohm meter measurement was greater than 40 MΩ. During Hypot testing the cathode keeper shorted to cathode common. The Hypot reached its current limit of 2 mA at less than 20 V. Impedances less than 10 kΩ cannot be measured accurately with the Hypot due to the resolution of the analog voltmeter. Subsequent measurement with the digital ohm meter showed that the impedance was less than 1 Ω.

After the 8200 hour EMT2 test, up to 50 μm thick deposits were found on the upstream edge of the cathode keeper orifice [4]. Such deposits may have peeled away from the FT2 cathode keeper and shorted to the cathode during the Hypot measurement at 6408 hours.

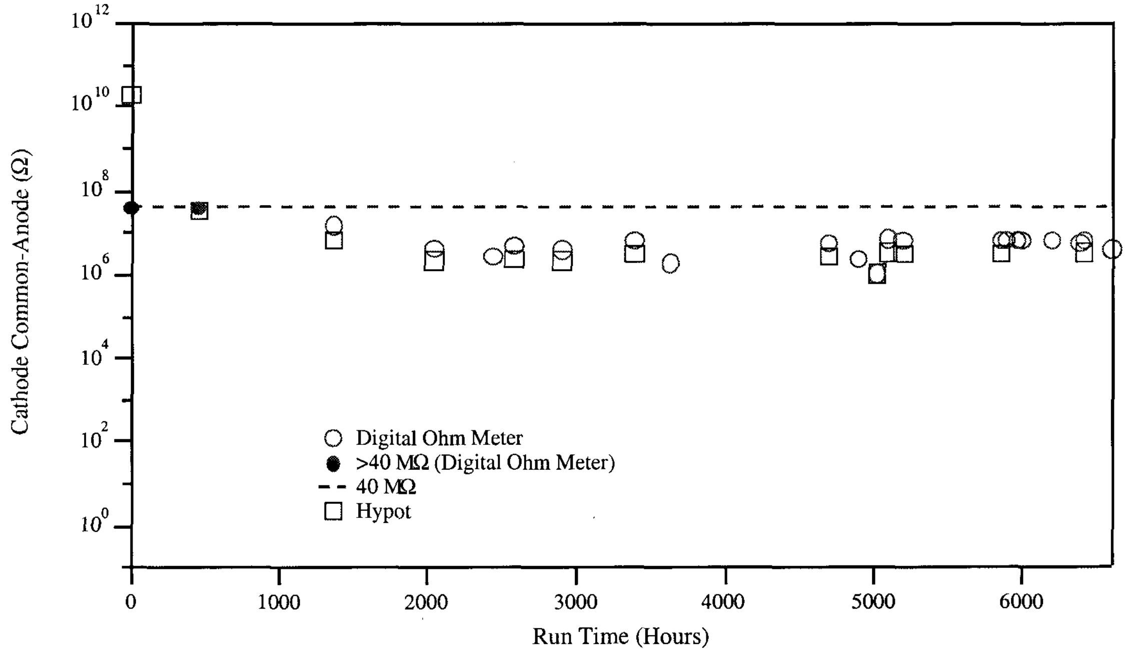

Fig. 22: Discharge Cathode Common-to-Discharge Anode Impedance

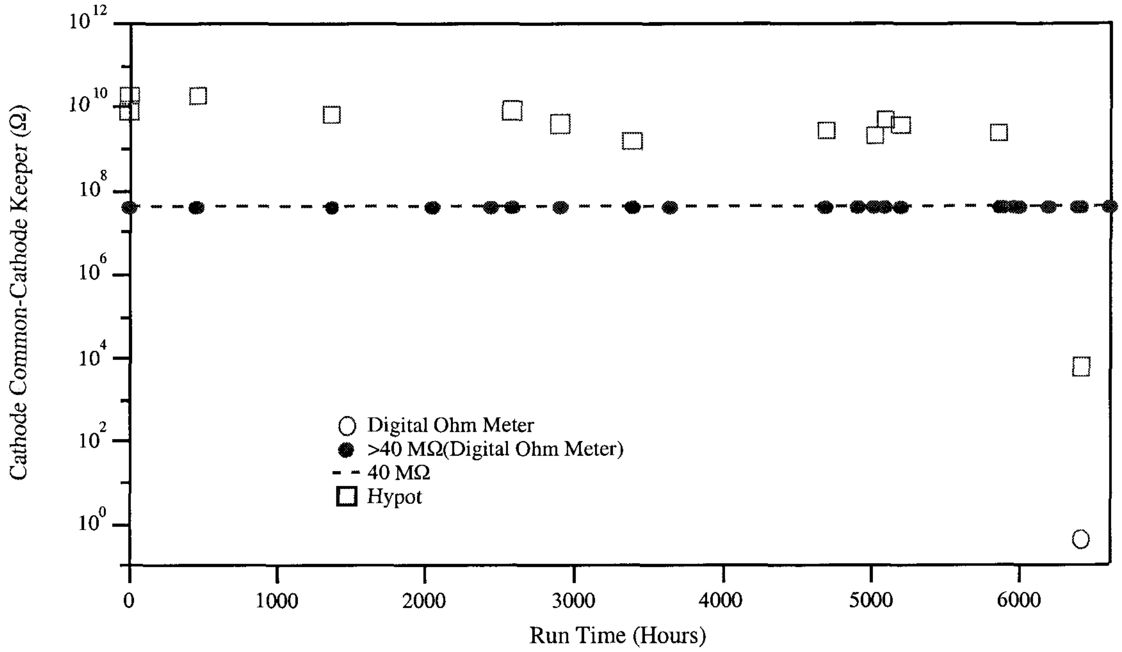

Fig. 23: Discharge Cathode Keeper-to-Discharge Anode Impedance

The voltage between cathode keeper and cathode common is monitored during thruster operation; typically it is 3 to 5 V. An intermittent short developed between cathode keeper and cathode common between 5850 and 6000 hours of the FT2 test; this caused the cathode keeper voltage to jump between ~3.5 V and ~0.4 V. After 6000 hours the cathode keeper voltage has remained at about 0.4 V. When the thruster was turned off and cooled down, the cathode keeper-cathode common short cleared and the digital ohm meter reading at 6597 hours was greater than 40 mΩ.

Since 5977 hours, the discharge has been more difficult to ignite on FT2. Prior to this the discharge could be ignited with the 50 V open circuit laboratory power supply. After

5977 hours, the discharge could not be initiated with the 50 V supply and the 250 V start supply has been used. Apparently electrostatic forces cause the flake to move and short cathode keeper to cathode common during start attempts. Although it is more difficult to ignite, the discharge is igniting at a lower voltage than the 650 V available from the start supply on DS1. While the loss of electrical isolation between the cathode keeper and cathode common is undesirable, it is not expected to result in thruster failure. Modifications to the cathode design should eliminate this problem in future thrusters.

8. Conclusions

Over 6,700 hours of operation have been accumulated on the DS1 flight spare thruster (FT2) during an on-going test. The thruster is performing well and no problems which would preclude processing 125 kg of xenon with this thruster have been identified. However, one area of concern is degradation of electrical isolation between the discharge cathode keeper and the discharge cathode common. This has resulted in the inability to ignite the discharge with a 50 V laboratory power supply which had been used prior to the loss of electrical isolation. Since then a 250 V start supply has been used to start the discharge. This is still less than the 650 V available for starting the discharge on DS1. Slightly poorer discharge chamber performance during the first 3900 hours and again after throttling to 1.5 kW for FT2 compared to that of EMT2 has been observed. In addition the electron backstreaming limit for FT2 is 6 V lower (worse) than that of EMT2 during full power operation. During operation of the flight spare thruster at 1.5 kW, measurements indicate that very little erosion of the ion optics has occurred. Erosion of the ion optics system can lead to thruster failure either through inability to prevent electron backstreaming or due to structural failure of the accelerator grid. The lower erosion rates means that the ion optics has a long life at lower power levels.

9. Acknowledgments

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11. Biography

John R. Anderson is a senior engineer in the Thermal and Propulsion Section at Jet Propulsion Laboratory (JPL). He is presently conducting the life test of the DS1 spare flight thruster. He assisted with the 8,200 hour life test of the NSTAR engineering model ion thruster and investigated the potential use of buckminsterfullerene as a propellant in electric thrusters since joining JPL in 1992. He has a B.S. in engineering science and a Ph.D. in mechanical engineering from Colorado State University.

Keith Goodfellow

Jay Polk

Vince Rawlin has worked at NASA's Glenn Research Center for more than 33 years in the field of electric propulsion systems for near-Earth and planetary missions, specializing in gridded and gridless electrostatic ion thrusters. He has primarily contributed to the design and development of high specific impulse gridded ion thrusters and their operation in large vacuum facilities leading to flight validations. He has also consulted to other NASA and government agencies, academia, and industry, especially manufacturers and users of gridded ion sources for ground and space applications and has been Contract and Grant Technical Monitor for procurements in electric thruster research. His major accomplishments include the development of hollow cathodes for SERT II and SEP mercury ion thrusters, the pioneering of dished ion optics for high thrust/power 30-cm dia mercury ion thrusters, and the identification of thruster life-limiting erosion mechanisms and solutions to obtain required lifetimes.

James S. Sovey is a research scientist in the On-Board Propulsion Branch at the NASA Glenn Research Center. Mr. Sovey joined NASA in 1962 and has specialized in the technology development of resistojets, arcjets, and ion propulsion systems as well as ion sources applied to industrial applications. From 1992 to 1999 he served as the NASA GRC manager of the Thruster Element for the development of the ion thruster and power processor flown on the Deep Space 1 spacecraft. He holds B.S. and M.S. degrees in physics from Marquette University.

Mike Patterson